I

Leonardo da Vinci and Franz Reuleaux: Machine Engineers

I.1 INTRODUCTION

The 21st century has been called the Information Age, a term that evokes images of cell phones, laptop computers, pagers and cell towers. Television and public flat panel screens in stadiums and airports confront us with flashing images, fantastic color shapes and ciphers offering information and visual promotions as if in some ethereal science fantasy world without need of energy or inertia. However behind the virtual worlds of the Internet, machines are still with us, often hidden behind shiny plastic and chrome or under the basement, closeted, silent and sentinel. Contrary to post millennium hype about the dominance of information technology, or IT, in the new millennium, our lives continue to be dependent on machines to transport us, cool and heat our homes, provide light and manufacture the very symbols of the IT Age.

There are of course machine aficionados such as clock collectors, motorcycle and car enthusiasts and children who love to play with LEGO® toy robots. But for most people, machines are hidden from their daily life. Machines are so reliable that we take them for granted, out of sight and out of mind unless they fail or some tragic plane or train crash forces us to face the reality of the world of energy and inertia. Some machine-based TV shows featuring flashy, chrome-built motorcycles have appeared recently and *Zen and the Art of Motorcycle Maintenance* has made a small comeback. But for the public and press the *Machine* has lost its power and symbolism in the postindustrial world. In addition, our knowledge of how and why machines work or what components they are made of has also declined in recent decades.

The complexity of modern technology is a hallmark of our age. We have created large networks for energy, communication and transportation that involve millions of components that seem to act as intelligent systems beyond

the capacity of the average human to contemplate. Machines are an important sub-class of these complex technologies. The Boeing 787 airliner for example is said to have over a million parts. The average automobile is made up of more than 20,000 parts and an office copy machine has over a 1000 parts counting all the miniature components of electronics in these devices. How did humankind learn to create, design and produce these complex technologies? It is a topic as important as the history of art or the history of the social and political milieu in which these technologies appeared.

This book is about our machines and their evolution over the centuries as seen through the lives of two engineers who became symbols of their own machine age, Leonardo da Vinci, an Italian artist-engineer of the Renaissance, and Franz Reuleaux, a German engineer-scientist of the late 19th century Industrial Revolution. It is a story of the beginnings of the scientific study of the machine, its codification into a language of invention and its deconstruction into basic machine elements. It is not a story of lone geniuses and machine inventors working in isolation. It is about the evolution of knowledge that originated in guilds and workshops, was handed down across the centuries in machine-books by artist-engineers and was finally liberated and promulgated through the use of mathematics and scientific principles.

The modern origins of the Machine Age of the 19th century began in the Renaissance in 15th century Italy. In Siena and Florence, artist-engineers such as Mariano Taccola, Francesco di Georgio Martini, and Leonardo da Vinci, produced collections of drawings of hundreds of machines and machine elements. Some drawings were published in book form as was the case of Taccola and Francesco di Georgio, while those of Leonardo remained in manuscript form well after his death. Leonardo's manuscripts were broken up and were subsequently dispersed throughout Europe. Some of the more famous Leonardo manuscripts that contain machines are the *Codex Atlanticus* in Milan, *Manuscript B* in Paris, and the *Codex Madrid I* in Madrid, Spain. The first two contain the famous drawings of flying machines. However the *Codex Madrid* is unique in that it marks the first attempt to deconstruct machines into basic machine elements or mechanisms or what Leonardo called 'elementi macchinali'. Had Leonardo actually published this work, it might have accelerated the development of machine design. Also the *Codex Madrid* with close to a 1000 drawings of machines and machine elements was lost for more than a century in the National Library of Spain and only rediscovered in 1965.

Recognition of Leonardo's work in science and technology emerged slowly at first through reproductions of his drawings in the early 19th century

Figure I.1. Portrait of Leonardo da Vinci [1452–1519]

and accelerated at the end of the 19th century with publication of facsimiles of the *Codex Atlanticus* in Milan and the Leonardo Notebooks in the Institute of France. As early as 1864, a few German engineers had access to the variety of mechanisms in Leonardo's drawings, one of whom was the famous 19th century mechanical engineer, Franz Reuleaux [1829–1905] of Berlin.

Shortly after the *Codex Madrid* was rediscovered in 1965, the da Vinci scholar Ladislao Reti translated the text into English and published several popular books on 'Leonardo the inventor'. He showed that da Vinci had attempted to compile a basic compendium of machine elements. To compare Leonardo's drawings of machine mechanisms with modern machine design books, Reti choose the list of machine elements proposed by Franz Reuleaux in his popular, 19th century book on machine design, *The Constructor*, first published in 1864 and translated into four languages and four editions. In the present book we have expanded on Reti's thesis that Leonardo had anticipated the codification of machine design in the 19th century. In the process

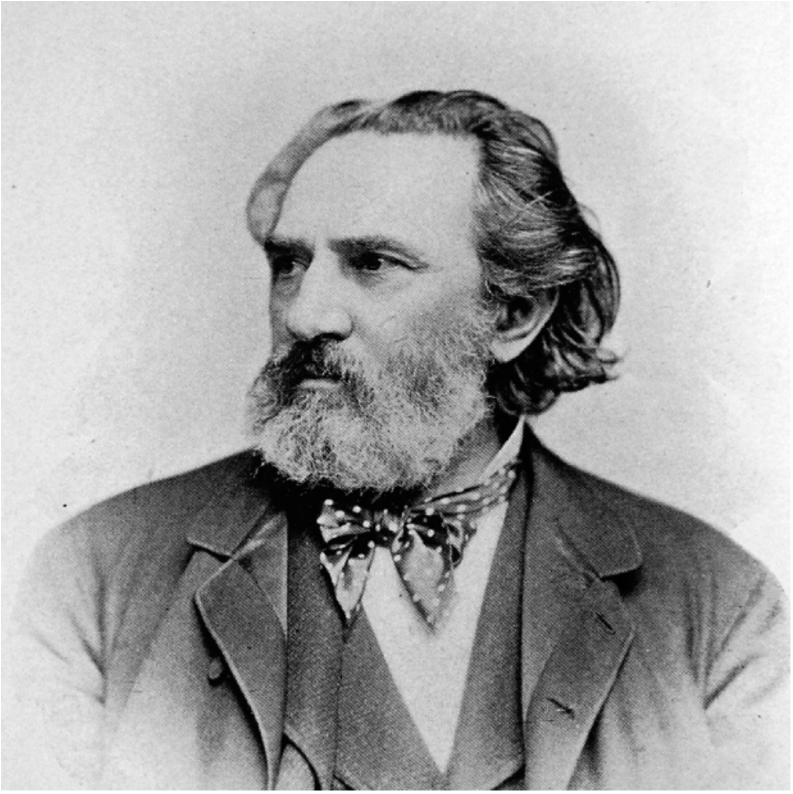

Figure I.2. Portrait of Franz Reuleaux [1829–1905]

we hope to evaluate the extent of Leonardo's influence on the education of late 19th century machine engineers.

One of our principal themes is that Leonardo da Vinci was a key node in a network of artist-architect-engineers, which passed on an unbroken chain of knowledge on the nature of machines through four centuries.

One of the fundamental questions of human evolution is how mankind learned to create the almost infinite variety of complex machines. Franz Reuleaux sought to address this question in his study of the theory of machines. The principles of design and building of machines was also a prime interest of the Renaissance engineers. Reuleaux raised a related question in 1885 on whether the capability to create complex technologies is more natural to certain races, ethnic groups or people from certain geographic areas. (Reuleaux's essay was a precursor to a contemporary book on a similar theme, *Guns Germs and Steel*, by Jared Diamond, 1999.) Reuleaux argued that the creation of an advanced technical society was not a matter of ethnicity but

depended on the commitment of that society to educate all its citizens on the truths of science and the process of rational thought. Leonardo in his time espoused a related theme, namely that the ability to invent new machines involved an experimental search for scientific truths and the use of mathematics to codify those truths.

In the last century we have witnessed the spread of the knowledge and ability to create complex technology to all cultures, races and geographic areas of the globe to the point that our new technical endeavors involve the entire human race. This transformation of creativity from the mind of an individual to a global collective technology has a long history that spans three or four millennia. Two important periods of technical history that witnessed a revolution in the process of creation of new technologies and in the creation of new machines in particular, were the Renaissance of the 15th and 16th centuries and the Industrial Age of the late 18th and 19th centuries.

The Machine Age of the 18th and 19th centuries marked the beginnings of the profession of mechanical engineering. Franz Reuleaux was one of the major theorists on the philosophy of machine design who taught in both Zurich and Berlin. He is credited with bringing order to the welter of inventions and hundreds of new machines that emerged in the industrial revolution by proposing that all machines are constructed of basic '*constructive elements*' and basic '*kinematic chains*'. He enumerated six basic topologies of these machine elements, called kinematic mechanisms that determine the motions within machines; *crank* chains, *screw* chains, *wheel* chains, *pulley* chains, *ratchet* and *cam* kinematic chains as illustrated in Figure I.3.

In his famous book *Kinematics of Machinery* (1876), he also proposed a list of 22 building blocks of machines. In a companion book translated as *The Constructor* or 'The Designer' (1861–1893), he gave detailed formulas and figures on how to design each of these basic machine elements in this list (Figures I.4a and b). To complement these books Reuleaux designed and built 800 models of brass and iron as a museum of machine mechanisms in Berlin. He authorized several workshops to reproduce these models for teaching engineers and inventors and a number of sets of models were sold in Europe, North America and Japan (see Figure I.5). Many collections never survived the destruction of World War II including the original Berlin Collection. Approximately 60 models are in the Deutsches Museum in Munich, 113 models are in the University of Porto, Portugal and 230 models are in the Kinematic Mechanism Collection of Cornell University.

The beginnings of the deconstruction of machines into basic elements of machine design began in the Renaissance where parallels to Reuleaux's for-

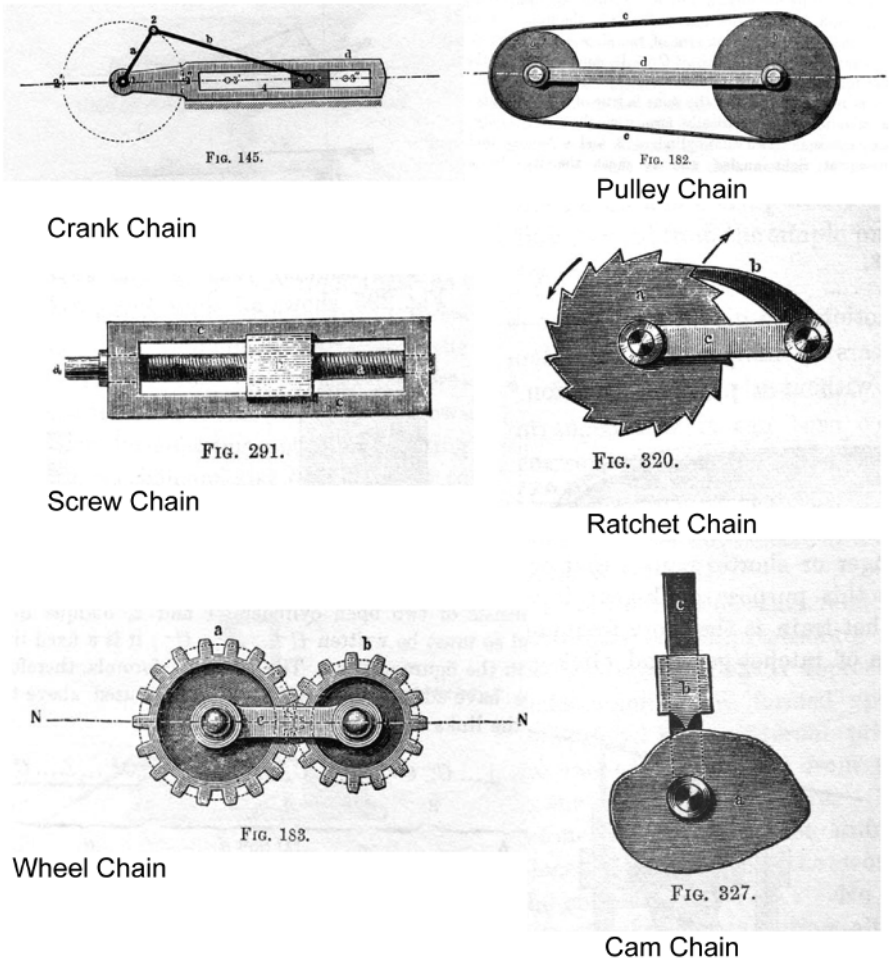

Figure I.3. Reuleaux's six classes of kinematic mechanisms from *Kinematics of Machinery* (1876)

mal classification theory can be found in the drawings of Leonardo as shown in Figures I.4a and b. In this book we compare the variety of machine elements of the Industrial Age as codified in Reuleaux's models and books, with the known machine components of Leonardo's day. There is no claim that Leonardo da Vinci invented all or any of these components. There is reason to believe that many of the drawings simply recorded the devices produced in workshops in his time. Of course, it is likely that some of his combinations of mechanisms describing complete machines were true inventions of Leonardo. After his death, several picture books of machines were published

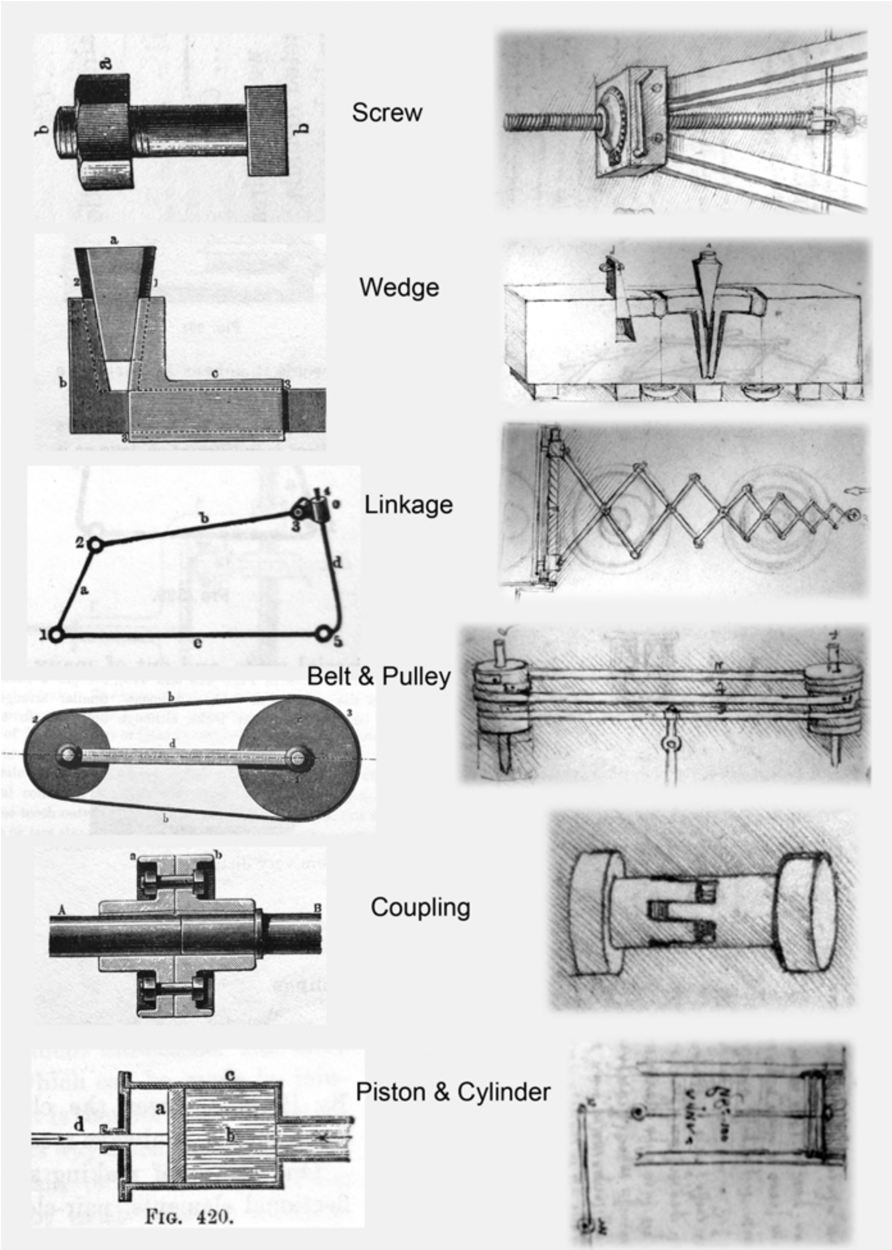

Figure I.4a. Comparison of kinematic elements in machine design from the books of Franz Reuleaux (on the left) and drawings of Leonardo da Vinci from the *Codex Madrid I* (on the right). See also Table I.3

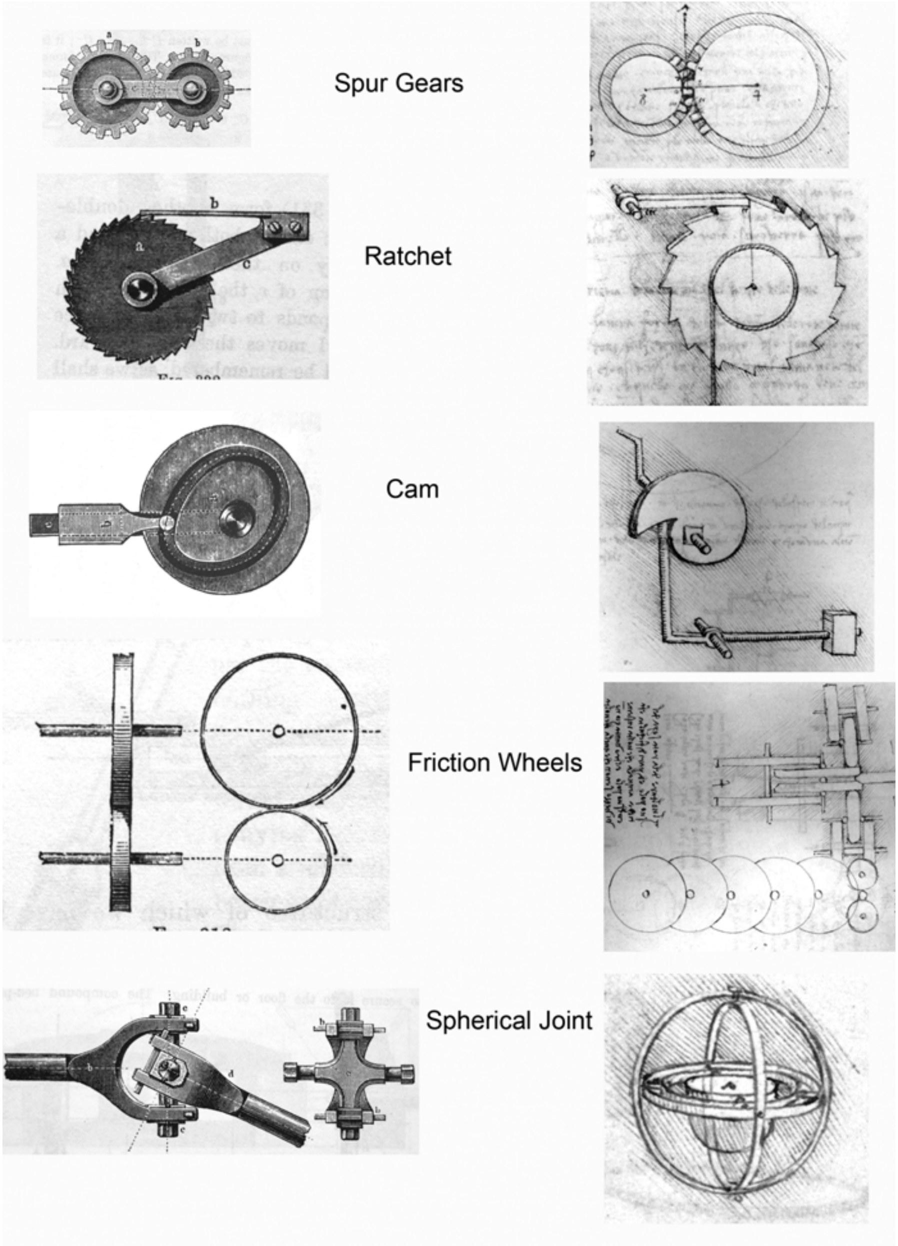

Figure I.4b. Comparison of kinematic elements in machine design from the books of Franz Reuleaux (on the left) and drawings of Leonardo da Vinci from the *Codex Madrid I* (on the right). See also Table I.3

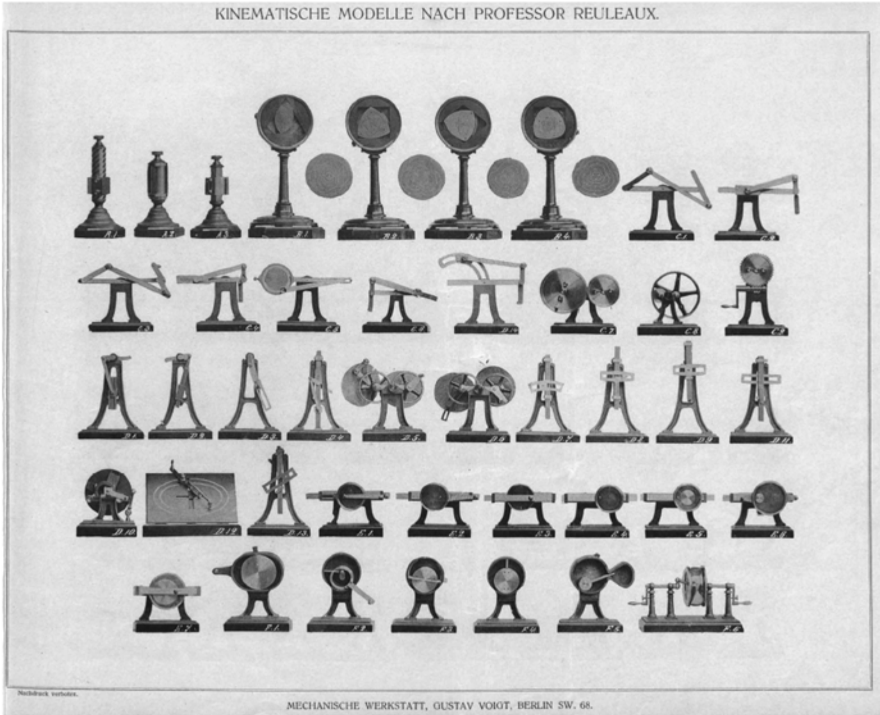

Figure I.5. Selection of 350 kinematic models from Voigt Catalog of Reuleaux Models (c. 1900)

such as that of Agostino Ramelli in 1588 called *Le diverse et artificieuses machine* (The Various and Ingenious Machines of Agostino Ramelli). Ramelli recorded complete machines employing many of the ‘elementi macchinali’ that appeared in Leonardo’s drawings, which Ramelli had not likely seen. It is highly probable that the bulk of the elements in both Leonardo and Ramelli’s works were common knowledge of craftspeople and machinists that had been handed down over the centuries with origins in Babylonian, Egyptian, Greek, Roman, Chinese and Arab civilizations that preceded the Renaissance revival of scientific and technical progress.

Late in his career, Franz Reuleaux (1884) edited a nine-volume, encyclopedic work called in English, *The Book of Inventions*, chronicling the history of technology. A forerunner of a later work by Singer et al. (1956), it begins the story of invention among primitive peoples and ancient civilizations and traces the path of technical progress into the machine age of the late 19th century. In a time when the hero-inventor paradigm was popular in the 19th

century American press, Reuleaux pursued the idea that it takes a society to produce a machine or any new technology.

The evolution of the process of technical creation is often ignored in conventional history books, explained sometimes in terms of individual genius-inventors and scientists. Careful study of the history of any technology such as clocks, computers, engines, or material processing will reveal a long path of evolution over many centuries, involving both the famous and not so famous inventors and craftspeople. In the creation of mechanical machines, this development was refined into a rational method that was codified in textbooks, design codes and in engineering societies. This codification enabled the diffusion of this methodology to all parts of the world. This was a remarkable achievement in the history of technology. This book will attempt to present a guide to a small part of this evolutionary path to the creation of technical complexity in our modern world.

In the frontispiece of Reuleaux's edited Volume VI, *Book of Inventions*, there is a beautiful lithograph showing the various components of machine design, gears, belts and pulleys, wheels and pistons, with an angel hovering and controlling the motions of these machine parts (Figure I.6). Both in Reuleaux's Industrial Age and the Renaissance, machines were often viewed in the same context as architecture and art and that the invention of new machines involved the same mindset and skills as that of the artist. This is another facet of comparison between Leonardo and Reuleaux that we will explore in this book.

Outline of this Book

This book consists of four parts; Part I, Sections 1–8, provide an introduction to the engineering careers of Leonardo da Vinci and Franz Reuleaux as well an assessment of the influence of the machine art of Leonardo on machine engineers and theorists in the Industrial Age of the 19th century. Part I also has a brief introduction to kinematics of machines and mechanisms for the reader not familiar with this subject.

Part II, Sections 1–21, consists of a survey of the evolution of machines and their design methodology from the time of the Renaissance to the beginning of the 20th century. We discuss the roles of mathematics, mechanics and art in the process of machine invention and design and try to understand Leonardo's methodology as a machine engineer. We posit a list of five essential factors in the invention of a successful machine and review how these conditions were met in the development of the Watt–Boulton steam engines

Figure I.6. The Angel of Machines: from *Buch der Erfindungen Gewerbe und Industrien*, or Book of Inventions, Vol. 6, 1887, F. Reuleaux, Editor

of the late 18th century. We end Part II with a discussion of machines, robots and biology and the early development of flying machines.

Part III is a kinematics mechanism reference section, containing detailed comparisons between the machine drawings of Leonardo da Vinci and the kinematic models of Franz Reuleaux.

Part IV has the usual list of cited references but also contains lists of texts on Leonardo da Vinci, kinematics and the work of Franz Reuleaux and his school of machine theorists. The Appendices in Part IV contain a valuable summary of 'Theatre of Machines' books from the 15th to the 19th century. This section also contains a set of problems and projects for students and instructors of design and history of engineering courses.

Parts I and II were written so that sections could be read or assigned for study in a somewhat random order. The author hopes that the serial reader will not be too critical of a certain amount of redundancy in the background information.

I.2 MODERN APPLICATIONS OF KINEMATICS: LEONARDO IN YOUR TOOTHBRUSH

The current era of technology has been called the microelectronics, and nanotechnology revolution. Contemporary high technology is identified with computers, cell phones and other communication devices. Macro-technology, in the form of high-speed trains such as the 240 km/h (150 mph) Acela Amtrak machines in the US, and the 430 km/h (269 mph) German-Chinese Transrapid MagLev train in Shanghai or the Boeing 787 and the Airbus 380, the largest airliner in the world that will enter service in 2007, are almost invisible in the media. Machines today are taken for granted even though we all ride in cars or planes, brush our teeth with them and copy and print our documents with machines (see e.g. Table I.1). Thus it is hard to imagine the excitement that machine technology produced in the 19th century.

The American celebration of the Machine took place at the Centennial Exposition in 1876 in Philadelphia. The centerpiece of this world's fair was the grand Machinery Hall with its hundreds of machines on display including the largest steam engine in the world, the Corliss Engine. President Ulysses S. Grant was on hand to turn the valve that started the huge engine and power the rest of the machines through a network of moving belts and pulleys. Over seven million people attended the Philadelphia world's fair in six months, an astounding figure in an age without automobiles. Such was the attraction of technology and machines a century ago. Though many Americans spend more each year on new sport utility vehicles than on personal computers, the news about these new vehicles is often on the global positioning (GPS) map system and the on-board portable video for the children than about any new mechanical technology, let alone the mechanisms that comprise the heart of the machine.

Modern consumer packaging has largely placed the technological nucleus of machines out of sight. This is especially true of the set of mechanisms that are linked together to make the machine transform energy into useful applications. Yet mechanisms and the science of kinematics upon which the design of these devices depends are very much at the heart of many of the modern technologies that we shall review in this section. Beginning in the time of Leonardo da Vinci, and culminating in the work of Franz Reuleaux in the 19th century, engineers were able to view the construction of machines as a set of interconnected modular elements called 'constructive elements' by Reuleaux or 'elementi macchinali' by Leonardo.

An important contribution of Reuleaux was the recognition that mechanisms in machines consist of a kinematic chain of simpler elements. A kine-

matic mechanism is one in which the motion of one element determines the motion of all the other parts. Thus in a child's tricycle the motion of the pedal crank determines the rotation speed of the three wheels and the forward speed of the tricycle. The interrelationship between the motions of all the parts is determined by the geometric constraints between the parts, such as the size of the pedal and the diameter of the wheels. Any machine can be deconstructed into sets of basic mechanisms in the same way that a sentence is the sum of words with grammatical relationships. Reuleaux developed a language of symbols for this deconstruction of machines in the hope that it would help in the invention of new machines. In the newly discovered *Codex Madrid* of Leonardo, there is evidence that da Vinci had planned to set down a basic set of mechanisms through the use of technical drawings, which could be used by engineers and designers to construct new machines. Unfortunately like many of his unfinished projects, Leonardo never published such a book and his notebooks with these drawings were scattered in private and Royal Libraries and some were lost for many centuries.

In the Renaissance, the principal applications of machines were for warfare, construction, canal digging, water pumps, clocks as well as water wheels for transmitting energy and machines for producing textiles as illustrated in the notebooks of Leonardo da Vinci. In Reuleaux's time, the steam engine was replacing water as a prime mover and the applications ranged from pumping water out of deep mines, blowers for iron production, railroad engines, steam ships, as well as agricultural and production machines in the 19th century. At the same time mechanisms began to be employed for calculating machines, thus anticipating the age of computers.

In the current age, mechanisms and the theory of kinematics find application in another set of technologies that did not exist in Reuleaux's time. These include automobiles, aircraft, space vehicles, robots, assembly line manufacturing as well as in electronic printers and cameras. And as illustrated in Figures I.7 and I.8, modern mechanisms can be found at either a scale of meters or micrometers.

In the 'information age', a new era of machine design has emerged called '*mechatronics*', which combines the three fields of machine design, electronic control and artificial intelligence and computer science. In the new era of mechanical design, mechanical components of high strength and endurance are still required to run at high speeds and carry high torques, but many of the control linkages found in 19th century machines are now replaced with electromagnetic and optical sensors and the prime movers are often electromagnetic motors. In contrast to early 20th century control in machines, analog

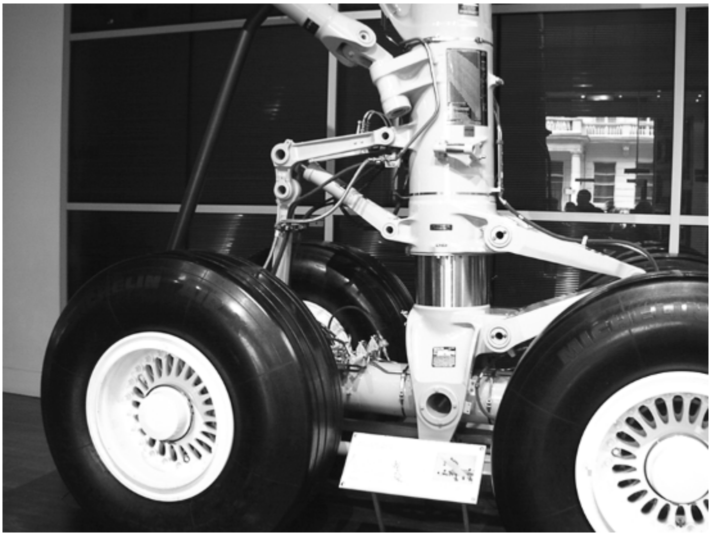

Figure I.7. Landing gear linkage for an Airbus jet. (Science Museum, London)

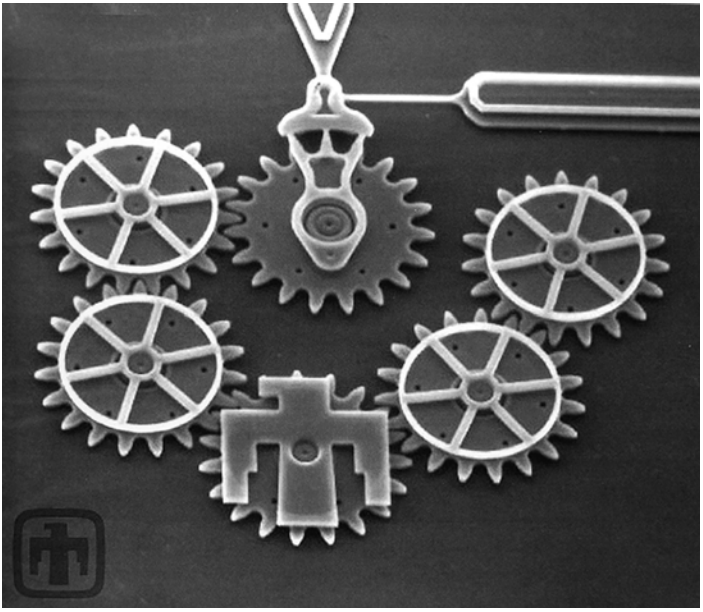

Figure I.8. Micro-electromechanical System [MEMS] gear train; Courtesy: Sandia National Laboratory

controllers have largely been replaced by digital electronics and associated microprocessor computer control. Modern robotic machines are often characterized in the media as emanating from computer technology. However key

components in robots such as the topology of the linkage, joints and end effectors are derived from the field of mechanism design.

There are thousands of modern applications of kinematic mechanisms, many of whose basic elements were known at the time of Leonardo da Vinci. Reuleaux and other machine engineers later codified these mechanisms, using mathematical principles in the 19th century.

From the Renaissance to the Industrial Age, machines were largely constructed from assemblies of fairly rigid objects such as gears, cams, screws, links and pistons with some use of flexible elements such as belts and springs. Today modern kinematic mechanisms can be made entirely of compliant elements, so much so that the line between machine and structure has become blurred. Also as illustrated in the gear array in Figure I.8, microelectromechanical systems or MEMS are using kinematic elements on a scale of microns, many of which use compliant mechanisms. At a much smaller scale of nanometers, molecular arrangements of molecules are being synthesized to function as kinematic mechanisms with screw and rotary motions.

Whether the scale is 1–10 meters as in the landing gear of jetliners (Figure I.7) or at the submicron level of molecular machines, the key design guideline of machine invention and creation is '*geometry and topology rules*'. Machines transform motion and in doing so transmit forces, energy and information. And although physical laws are essential to their operation, the geometric arrangement of machine elements is key to how successful this transformation of motion is. As we shall see throughout this book, geometric thinking was key to the design of machines for both Leonardo da Vinci and Franz Reuleaux.

Our final thought in this discussion of modern applications of kinematics is the roles that energy-based machines and information-based machines played in the evolution of technology. Throughout the period from the 15th to the 20th century, both types of machines were developed. Beginning in the 16th and 17th centuries, clocks and automata required the development of precision manufacturing to create accurate gearing and linkages, especially in digital devices such as clocks, calculators and arithmometers that later appeared in the 19th century. In the development of power machinery, especially internal combustion machines in the middle to late 19th century, the need to develop strong materials to resist high stresses and high temperatures pushed the development of materials engineering. Both technologies of precision fabrication and advanced materials came together in the aeronautical engines of the 20th century as well as in the information processing technologies of the early computer age. Most of the data storage of the late 20th and early 21st

Table I.1. Modern applications of kinematic mechanisms

Automobiles
Engine components: pistons, crankshaft, cams, valves
Gear transmission: planetary gears
Rear axel: universal joint and differential, ball bearings
Brake system
Doors, hatches, hood
Aircraft
Fuselage: passenger and cargo doors and hatches
Landing gears
Wings: flaps, control surfaces, ailerons
Engine: bearings, gearing
Robotics
Manipulator arm linkage
End effecter, grippers
Hydraulic actuators, pistons and valves
Bio-engineering
Artificial limbs: linkages and cable systems
Artificial hands
Joint replacements: bearings
Mobile chairs: wheels, brakes
Space Technology
Spacecraft antenna: folded structures
Nose cone shroud
Solar panels
Planetary rover vehicles
Space shuttle robotic arm
Manufacturing
Machine tools: lathes, milling centers
Assembly line components
Machining centers
Textile production machines
Electronics and Computer Technology
Cameras: lens focus mechanism
Disc drives, microdrives
Video recording and playback devices
Computer printers: belt drive mechanisms

Table I.1. Continued

Food Production
Farm machinery: plowing, seeding, harvesting
Crop picking machines
Food packaging and bottling machines
Construction Machines
Cranes: pulleys, cables
Backhoes, loaders
Cement mixing machines
Tunnel boring machines

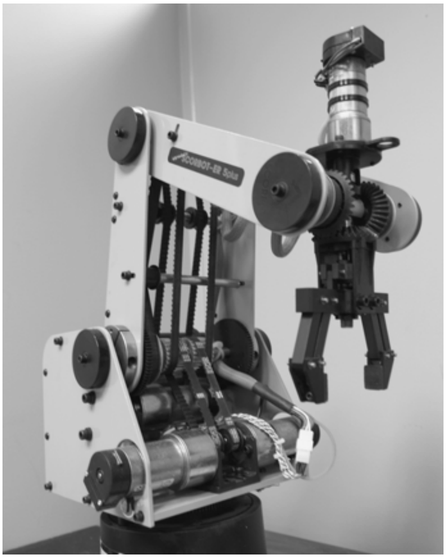

Figure I.9. Modern robotic manipulator arm with end effector gripper

century is on rotating disc machines in which the read-write head rides above the surface at less than a micron. The modern creation of machines spans not only a wide range of applications (listed in Table I.1), but a wide spectrum of scales from 10 to 10^{-9} meters and a wide spectrum of energy densities.

Leonardo in Your Toothbrush: Kinematic Mechanisms in Daily Life

Two popular products are the ‘Spin-Brush’ or motorized toothbrush and the ‘iPOD’. In the latter, wires in listeners ears lead to a small box with an electronic chip that stores music from the web sometimes on a micro hard disc.

The 'iPOD' is an icon of 21st century information technology. In contrast are the wireless, motorized toothbrushes initially costing $30–50 that can now be bought for a few dollars or euros. Some of these dental devices also embody modern mechatronics and electronic chips, but most possess kinematic mechanisms that have roots in the Italian Renaissance 1450–1600.

An example of one of the first motorized toothbrushes is the upscale model by the German company Braun, circa 2001, shown in Figure I.10a. This is a marvel of miniature *mechatronic* design. The brush sits in a holder (not shown) that picks up electrical power from an alternating voltage outlet in the wall. A coil in the brush converts the ac power to dc current that charges the batteries using an electronic circuit board in the handle. This is the '*-tronic*' part of the *mecha-tronic* machine. The battery drives a small continuous speed electric motor. The goal of the machine design is to convert the motor motion into oscillating motion in the small brush at the end that cleans your teeth. The mechanical parts consist of three kinematic mechanisms:

(i) a brass gear-pinion mechanism;
(ii) a four-bar linkage;
(iii) a three-dimensional ball joint mechanism.

These mechanisms produce the following change of motions in your toothbrush:

(I) change of high speed continuous rotation into lower speed rotation;
(II) the crank in the four-bar linkage converts continuous rotary motion into oscillating motion in the follower link;
(III) the three-dimensional ball linkage converts oscillating motion about the vertical axis in the handle into oscillating motion about a transverse axis that 'spins' the brush; the final motion that helps clean the teeth.

Another dental product that costs much less than the 2001 Braun is the Crest '*Spin Brush Pro*' shown in Figure I.10b. Here there is no on-board rechargeable circuit: just a AA battery. In this device there are also three kinematic mechanisms:

(i) a plastic crown wheel gear and pinion mechanism;
(ii) a slider-crank mechanism with the crank and the drive link;
(iii) another slider-crank mechanism with the slider and the drive link.

These mechanisms provide the following change of motions in your toothbrush:

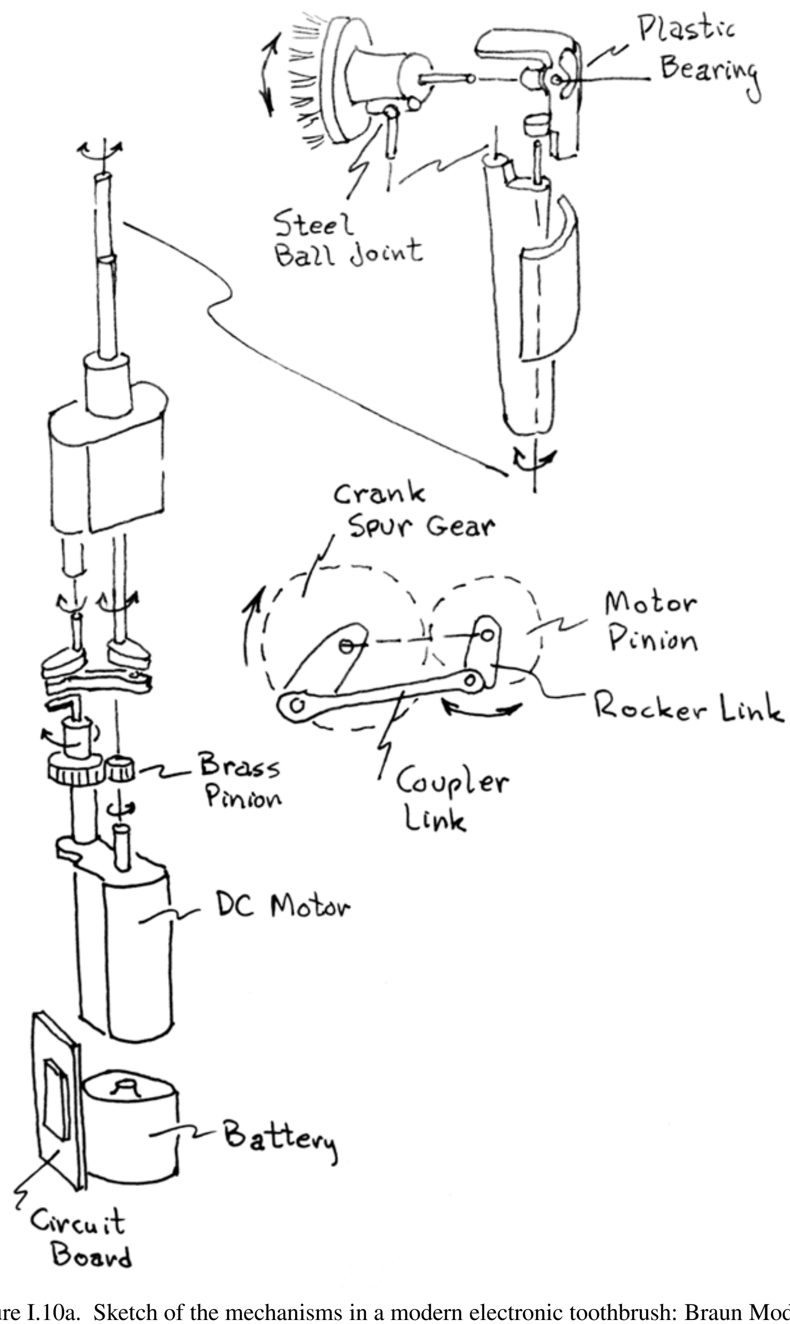

Figure I.10a. Sketch of the mechanisms in a modern electronic toothbrush: Braun Model

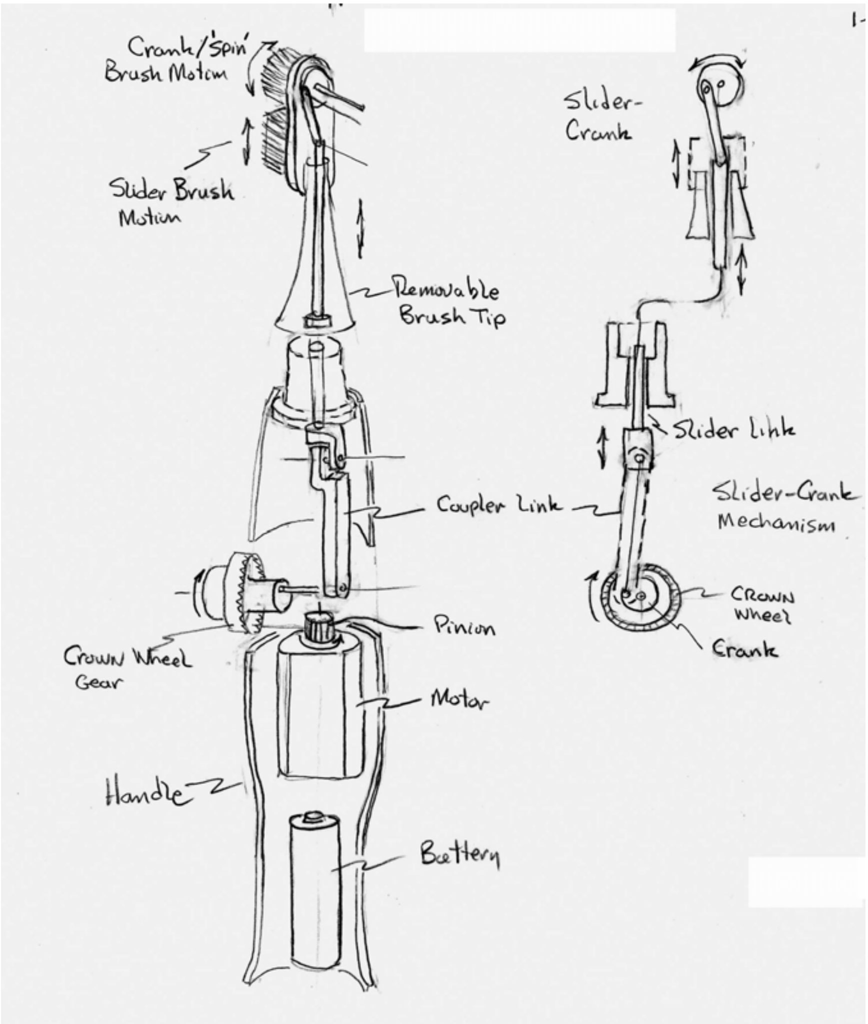

Figure I.10b. Sketch of the mechanism in a motorized toothbrush: Colgate Model

(I) the crown-wheel and pinion change high-speed motor rotation about the vertical axis into lower-speed motion about a transverse axis;
(II) the crank in the slider crank mechanism converts continuous rotary motion into oscillating motion of the slider along the vertical axis;
(III) the upper slider-crank converts the oscillating motion of the slider into oscillating motion of the brush.

It should be noted that the brush is really oscillating about a horizontal axis and is not spinning with constant speed, as the name would imply.

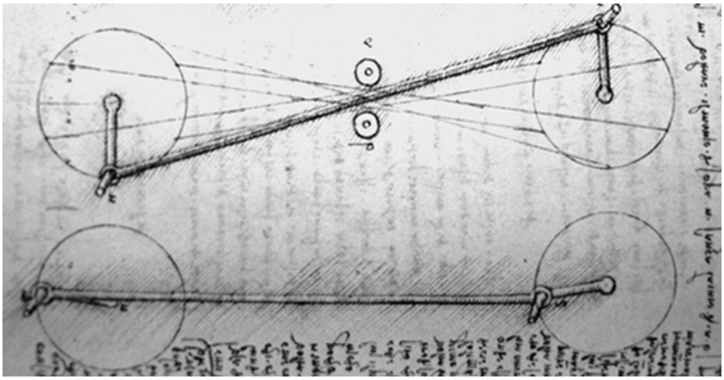

Figure I.11a. Four-link mechanism of Leonardo da Vinci (*Codex Madrid I*)

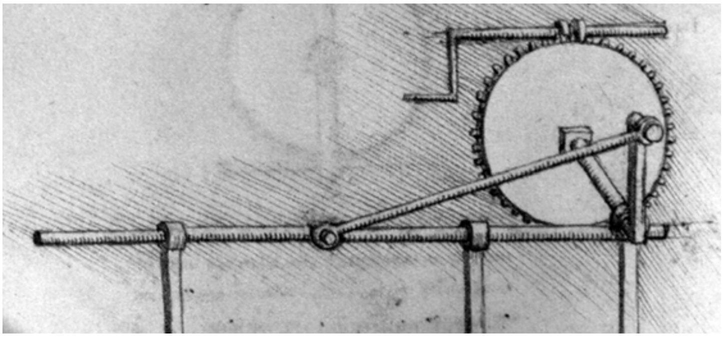

Figure I.11b. Slider-crank mechanism (*Codex Madrid I*)

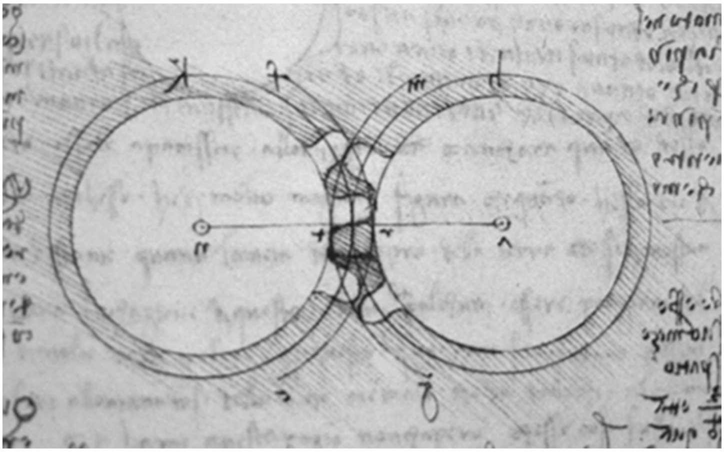

Figure I.11c. Gear and pinion (*Codex Madrid I*)

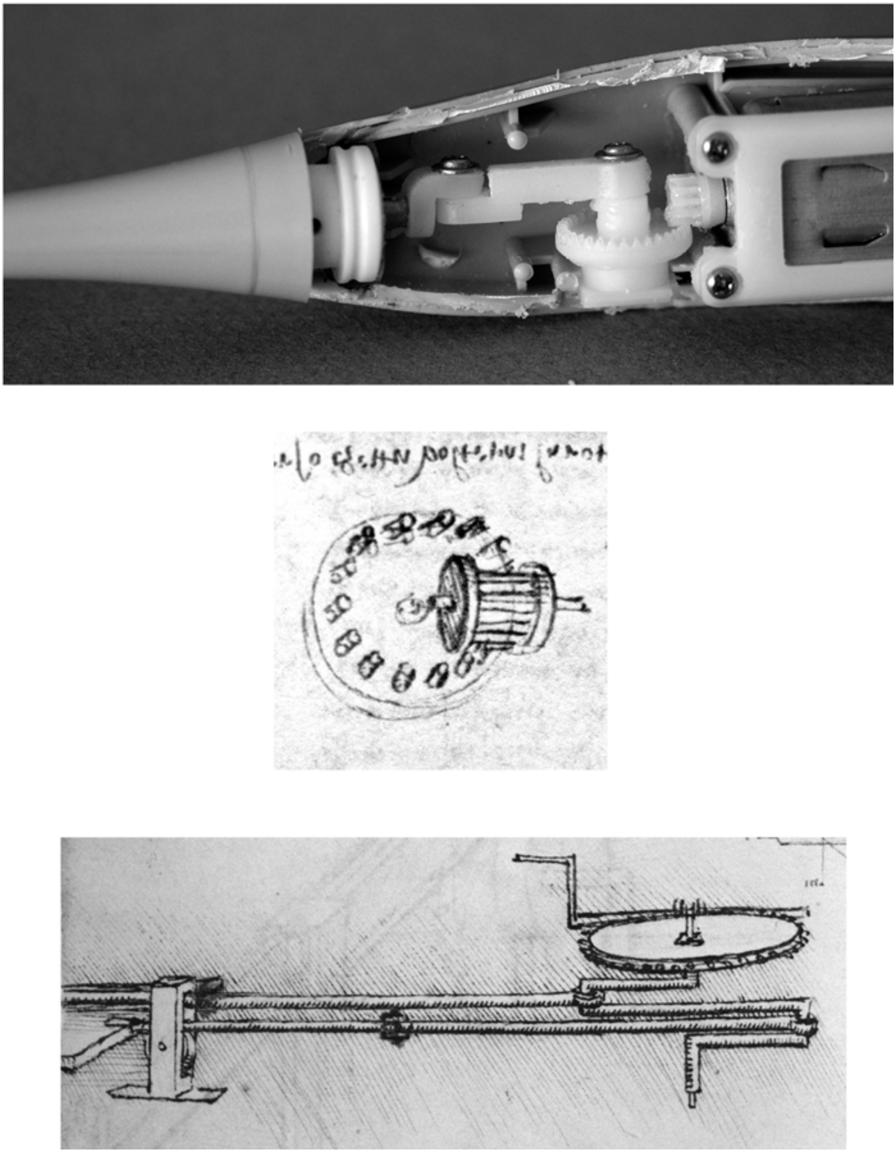

Figure I.12. Top: toothbrush with crown wheel gear and pinion and slider-crank mechanism. Middle: Crown wheel gear and lantern pinion of Leonardo da Vinci from the *Codex Madrid I*. Bottom: Double slider-crank mechanism and worm gear drive of Leonardo da Vinci from the *Codex Madrid I*

Although several manufacturers have secured patents on these devices, the sub- mechanisms that change the constant rotary motion of the motor into the oscillating brush motion can all be found in the machine books of the Re-

naissance notably in the drawings of Leonardo da Vinci. Two of the principal manuscripts with drawings of machines and mechanisms are the *Codex Atlanticus* in the Ambrosiana Library in Milan, Italy and the *Codex Madrid* in Spain. In these manuscripts one can find hundreds of drawings of machines, geometric exercises, architectural designs and textural descriptions and notes intermingled with the drawings. Although Leonardo's writings were thought by some scholars to have been designed for formal books on painting, machine design or bird flight, what survives is more or less the first sketches, ideas and musings of one of the principal icons of the Renaissance man.

There are many drawings of Leonardo of complete machines. But there are many other drawings of machine components that are used in all machines. In Leonardo's machine elements the focus is often on how the mechanism converts motion from one form to another as from continuous rotation of a water wheel into oscillating motion in a linkage in a textile machine.

The geometric principle of conversion of motion from one form to another, without regard to the forces, is called *kinematics* or the study of pure motion. This name was given by the French mathematician, A.M. Ampere, in the early 19th century.

Several of the toothbrush mechanisms can been seen in Leonardo's drawings from his *Codex Madrid I* as shown in Figures I.11. In Figure I.11a is a drawing of a four-bar mechanism and Figure I.11b shows a slider crank device. Another drawing is a pinion-gear pair (Figure I.11c) similar to the pair in the toothbrush shown in Figure I.10a. The difference between the two gear pairs in Figures I.10a and b is that the axes of rotation of the pinion-gear set are parallel in contrast to the crown wheel-pinion gears the axes of rotation are at an angle of 90 degrees to each other.

A motorized toothbrush with a slider-crank and crown wheel gear is shown in Figure I.12. Leonardo's drawings corresponding to these toothbrush mechanisms are also shown in Figure I.12.

I.3 DECONSTRUCTING THE MACHINE: CONSTRUCTIVE ELEMENTS OF DESIGN

The evolution of machine theory has some similarity with biology. By the middle of the 19th century, machines had been invented and built that had their own sources of energy, were mobile, and were undergoing a process of multiplication and evolution, becoming more complex with every new generation. To bring order to the welter of new machines, engineers began to search for ways to codify and classify these devices. Beginning in the 16th century, compendia of machines, such as those of Besson (1578) and Ramelli (1588), organized machines according to application, such as pumps, manufacturing machines, construction machines, etc. This methodology paralleled similar attempts to organize the biological world such as the *Systema Naturae* of Carolus Linnaeus in 1735.

Beginning in the 18th century, with Leupold (1724) and the French Ecole Polytechnique in Paris, another theoretical path to machine theory was opened that attempted to organize machines from a reductionist point of view based on modular elements. The *Codex Madrid* of Leonardo da Vinci provides evidence that Leonardo envisioned a similar deconstruction of complex machines into basic machine elements in the late 15th century. By the 19th century however, mechanisms began to be viewed as *motion-changing devices* and this path was formally codified by Charles Babbage of computer fame, Robert Willis of Cambridge and later by Franz Reuleaux. Reuleaux introduced ideas based on kinematic pairs, kinematic chains, and compound mechanisms. Other codifiers of machine systems however included *prime movers* and *automata*. In recent years new terminology have appeared to deal with the inclusion of electronics and computers into mechanical devices with terms such as smart machines, mechatronics and micro-electromechanical systems or MEMS.

The codification of machine design has been taken for granted in the history of technology. The creation and design of machines on a rational basis freed the industrial age from the secrecy of the guild and workshop and helped to diffuse this knowledge all over the world, changing once feudal societies like Japan into emerging industrial powers by the end of the 19th century.

To help in our discussion of the theory of machines we present a short list of concepts to be used in this book.

Constructive Elements of Machine Design

When many different machines are disassembled into their constituent parts, there is a surprising similarity in the types of parts common to different machines even though the machines have entirely different applications. Most machines have rotating parts such as shafts, bearings and bearing supports. Others have belts, chains and gears to transmit motion from one part of the machine to another. An example of the deconstruction of a machine is the first automobile of Carl Benz, 1885 shown in Figure I.13. Benz was trained at the Karlsruhe Polytechnique in Germany under Ferdinand Redtenbacher, the same professor of mechanical engineering under whom Reuleaux studied.

Although machine builders knew of many machine elements by the 18th century, Reuleaux attempted to summarize the basic set of elements common to most machines of his time and organized them according to geometric principles. This list appeared in his *Kinematics of Machinery*, (1875–1876), and also in his earlier *Der Constructor* (The Designer) (1861–1893). These '*constructive elements*', as Reuleaux called them, had been anticipated by Leonardo da Vinci, mainly in his unpublished *Codex Madrid*. Machine elements appear today in standard machine design textbooks and many have been modularized in subcomponent catalogs of manufacturers in the form of bearings, gearing, motors, etc. In Reuleaux's list of constructive elements are included both kinematic and load bearing elements. Gears for example represent kinematic elements whose principal role is to change and transmit motion, while shafts, axels and bearing pedestals are required to support loads, forces and torques in the machine.

Simple Machines

The ancient Greeks defined six types of so-called simple machines: the *lever*, *wedge*, *screw*, *pulley*, *wheel and axle*, *winch and inclined plane*. These machine elements were often viewed in terms of equilibrating and transforming forces. In Franz Reuleaux's classification however, the 'simple machines' are each kinematic pairs designed to change motion through geometric constraints. This new view of mechanisms, in terms of constraints, changed the way engineers viewed the design of complex machines in the late 19th century. The so-called 'simple machines' evolved when human effort was the major prime mover. Given the force limitation on a human worker, the simple machine such as the lever enabled the low force and large motion of the human to be transformed into the small motion and large force of lifting heavy objects such as stone for construction projects. With the evolution of water mills, windmills and steam engine mine pumps, the focus of machines

Deconstructing Carl Benz's First Automobile of 1885
Into Reuleaux's Machine Elements

Friction Wheels

Chain Drive

Belt Drive and Shifter

Bevel Gears

Cam Mechanism

Valve Linkage

Slider Crank Linkage

Piston and Cylinder

Flywheel

Figure I.13. First automobile of Carl Benz and the list of basic machine elements and mechanisms (c. 1885) (Courtesy of the Deutsches Museum, Munich)

shifted to the transformation of motion. Beginning with the French mechanicians of the Ecole Polytechnique in the late 18th century, the complex nature of the rotating, translating, alternating and ratcheting motions began to take equal importance with the forces and strength of materials issues in machines. This trend can also be seen in the drawings of Leonardo da Vinci's notebooks

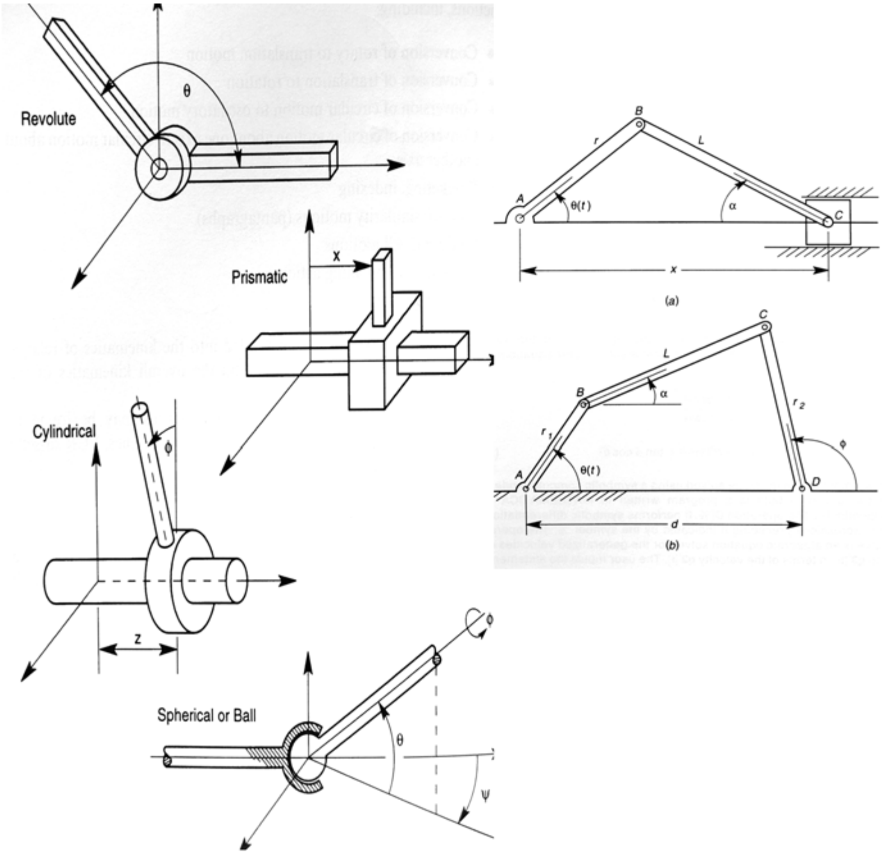

Figure I.14. Left: kinematic pairs; Right: (a) slider crank and (b) four-bar kinematic chains

that show his passion for the almost infinite topological variety of motion-changing mechanisms possible in complex machines.

KINEMATIC PAIRS

Reuleaux defined the constrained motion between two neighboring parts in a machine a *kinematic pair*, such as a piston in a cylinder of an internal combustion engine. (Figure I.14) These two parts can translate relative to one another called a *prismatic joint*. Two links connected by a pin joint on the other hand can only rotate with respect to each other in a *revolute joint*. A screw and a nut move in a helical motion relative to each other in a *screw joint*. Reuleaux called joints with surface contact such as a cylindrical bearing a *lower pair* constraint and he called joints with point or line contact a *higher pair* con-

straint. Several sets of linked kinematic pairs form the basis of a higher level concept in a machine called a *kinematic chain*.

Kinematic Chain

A kinematic chain is a connected series of kinematic pairs that form a closed loop or circuit, similar to an electrical circuit (Figure I.14). A bicycle chain is a set of cylindrical pairs or *revolute joints*. The closed loop of a crankshaft, piston rod, cylinder and cylinder block form one of the most ubiquitous kinematic chains found in all internal combustion machines called a *slider-crank chain* (Figure I.14a). The key property of the kinematic chain is the fact that the motion of one or more of the pairs in the chain, determines the motion of the parts in the rest of the chain. This places the design of mechanisms in the realm of geometry and mathematics.

Mechanisms

Mechanisms are simple or compound kinematic chains which are designed to transform motion. The motion of one link or element in the mechanism determines the type of motion in the rest of the links in the kinematic chain. For example, the slider crank kinematic chain in an internal combustion engine, i.e. the crank, piston and cylinder and connecting rod, changes the translation motion of the pistons into rotary motion of the crankshaft. In the early 19th century French school of kinematic design, mechanisms were classified as to how they changed motion; from say rotary into translation or from alternating into rotary motions. In 1826, Charles Babbage of England tried to develop a '*mechanical notation*' for mechanisms based on the transformation of motions in the machine.

Complex Machines

Several mechanisms coupled together, along with a source of motion or energy, form complex machines. An example is the first automobile of Benz (1885) shown in Figure I.13. It consists of several kinematic pairs (i.e. piston and cylinder block, or bevel gear pair) and coupled kinematic chains (e.g. the slider-crank formed by the piston or the chain drive coupled to the friction wheels on the ground), along with the chemical reactions of the fuel-air mixture that provide the force to drive the piston. In a mechanical clock however, the energy source is either gravity or an elastic spring and the motion is modified kinematically (i.e. geometric constraints) by a set of gears and often a ratchet wheel called an escapement.

Prime Movers or Engines

Prime mover machines are sometimes referred to as 'engines' as in gas turbine engines or internal combustion engines. From the 14th to 18th centuries, water power was a dominant adjunct to machines. Wind power in Europe had its origins in the late 13th century, especially in the region that is today Holland. Beginning in the 18th century and accelerating in the 19th century, the steam engine replaced windmill and water mill prime movers. By the 20th century, the steam turbine and electric motor had almost eliminated the reciprocating steam engine as a major prime mover. Franz Reuleaux played a role in the development of the Otto internal combustion engine of 1867 and one of his fellow alumni of Karlsruhe University, Karl Benz demonstrated its application in automobiles in 1885, a use that continues more than an century later. Electromagnetic motors of all forms, based on magnetic forces as well as actuation using hydraulic actuators have become principal drivers of many small to medium machines including robotic devices. In contemporary MEMS machines, micro-electric actuation based on direct electric forces finds application in acceleration sensors in automobile air bags.

Automata

The automated machine has a connotation of performing its tasks without human intervention according to an embedded set of instructions. Water driven automata were mentioned in ancient Greek literature as well as in Arab books describing machines of the 13th century. Before the industrial age *automata* devices were identified with clock-like mechanisms for telling time or driving mechanical musical devices as well as doll or robotic-like devices for entertainment. The player piano was a popular mechanical form of automata. In the Renaissance, engineers such as Leonardo da Vinci often designed fountains with time changing flows or moving props for stage productions and pageants as part of their duties for their patron. In the late 18th century, Jacquard designed punched cards to control textile machines. James Watt also invented a rotating ball speed controller for his steam engines. In the early 19th century Charles Babbage tried to build a machine with 15,000 parts to automatically generate mathematical tables for astronomy and navigation. By the 20th century, the idea of the *controlled-machine* and robotics reached maturity with the development of electronics.

Smart Machines, Mechatronics

Smart machines contain arrays of sensors and small computers called microprocessors to monitor the state of the machine and to adjust the actuation forces. *Mechatronics* is a term coined by Japanese engineers and reflects the interaction between mechanical, electrical and information or computer sciences to create a smart machine. *Smart machines* introduce new basic elements into machine design such as '*piezoelectric patches*' for sensing and actuation, *microprocessors* and embedded computers for handling information and decision-making or video-cam optical devices and MEMS sensors. The individual 'machine designer' has been replaced by an interdisciplinary *team* with specialists and generalists who piece together the hundreds of mechanical elements and electronic components in each new generation of machine. In this process, the 'team' pushes the boundaries of the previous model using both conventional machine elements and whatever new electronic, optical and software technologies have made it into the marketplace.

Deconstructing Leonardo's Machines

There are many books on the machines and inventions of Leonardo da Vinci. In this book however, we are focused on the basic language of machine invention – the fundamental machine elements and basic kinematic mechanisms. In the previous sections we have illustrated the deconstruction of a modern consumer machine and also the first automobile of Karl Benz and here we deconstruct one of Leonardo's machines for textile manufacturing. A question of interest to us is; to what extent was Leonardo aware of using a basic language of machine invention?

Of the hundred or more complete machines that he drew in his manuscripts, the Automated Spool-winding Machine is extremely interesting because it was not only drawn in a fairly complete way, but it also contained many machine elements and five kinematic mechanisms. Often Leonardo's machines are portrayed in the context of war and adventure; multiple crossbows, catapults, flying machines and an automated three-wheeled vehicle (see Table I.2). However, both Florence and Milan were important textile producing cities and Leonardo seems to have had some motivation to design several machines for wool and silk textile machines, so much so that there are two modern monographs describing his machines for the textile trade, Giovani Strobino's 1939 book in Italian, *Leonardo inventore tessile*, and Kenneth G. Ponting's 1979 book, Leonardo da Vinci, *Drawings of Textile Machines*.

Table I.2. Classification of Leonardo's machines by application

Manufacturing Machines	**Source**	**Construction Machines**	**Source**
Lathe	F1059r/381r.b	Cranes	F4r/1v.b
Screw cutting machine	Ms. G 70v	Swing bridge	F855r/312r.a
Rope making machine	F12r/2v.a	Canal dredge	Ms. E 75v
File making machine	F24r/6r.b	Canal lock gates	F90v/33v.a
Drilling machine	F34r/9v.b	Pumps	F20r/5r.b
Lens-grinding machine	F1057v/380r.b	Hydraulic screw pump	F1069v/386v.b
Needle-making machine	F86r/31v.a	Chain-of pots pump	F1069v/386v.b
Thread spinning machine	F1090v/393v.a	Pulley systems	F1102v/396v.g
Textile machines	F106r/38r.a	Windlass	F1112r/400r.a
Book press	F995r/358r.b		
Wine and olive press	F47r/14r.a	**Power and Transmission**	
Mechanical saw	F1059r/381r.b	Boat paddle wheels	F945r/344r.b
		Air turbine wheel	F46a-r/13v.b
Military Machines		Water power systems	F26v/7v.a
Bombs	F33r/9v.a	Spring-propelled cart	F812r/296v.a
Balistica	F145r/51v.b	Power transmissions	F26v/7v.a
Trebuchet	F160a-r/57v.a	Flying machines	F844r/308r.a
Catapults	F150r/54r.a	Human powered wheel	F1070r/387r.a
Armed chariots	Turin BB 1030		
Breech-loading mechanism	Ms. B 24v	**Measurement Devices**	
Giant Cross-bow	F149b-r/53v.b	Clock escapements	F96r/35r.a
Rapid-repeating crossbows	F182b-r/64v.b	Odometer cart	F1b-r/1r.bk
Steam-gun	Ms. B 33r	Weighing machines	Ms. A 52r
Multi-barrel gun	F157r/56v.a	Drawing compass	F696r/259r,a-b

Sources: *Codex Atlanticus*; Folio: F: New/Old numbers
Paris Manuscripts; Ms. A-M

The automated spool-winding machine can be found in the *Codex Atlanticus*, Folio 1090v, shown in an isometric drawing with shading and a cross-sectional view of the axel system (see Figure I.15). The main steps in textile production involve spinning thread, weaving, calendaring or pressing the cloth, beating the wool and dying the cloth. In the drawing of Figure I.15 the input motion is represented by a crank on the rear right side and the output is the thread wound on the spool on the right front side.

The action of the flyer is to twist the thread in a helical pattern on the spindle. To achieve this pattern the flyer and spindle are caused to rotate at different speeds and the flyer is made to move back and forth. Leonardo cre-

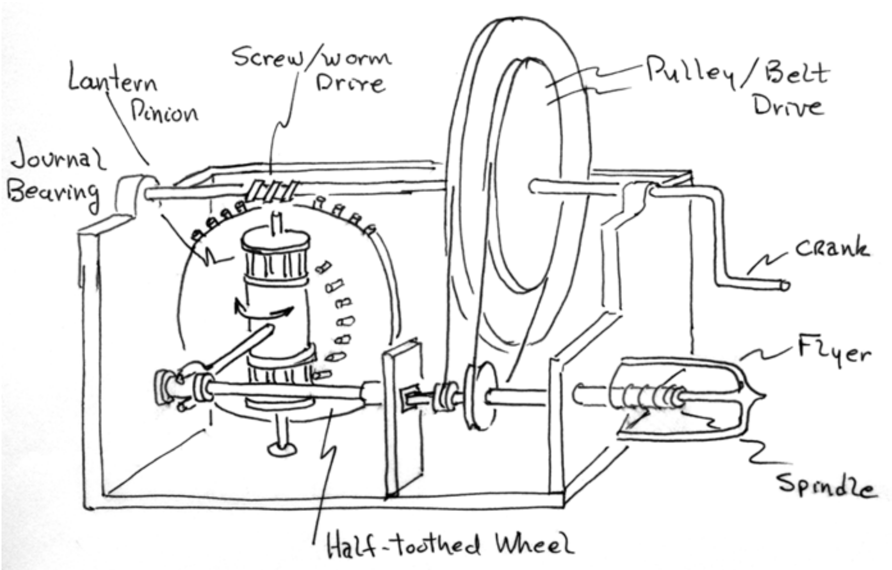

Figure I.15. Sketch of kinematic elements in Leonardo's textile spinning machine (based on *Codex Atlanticus*, Folio 1090v)

ated a speed differential in rotary motion of the flyer and spindle by using two different wheel-belt pulley drives, both fed off the same crank motion. To create a relative oscillatory motion of the flyer and spindle, the shaft is feed through a double-slider linkage coupled to an oscillatory cylinder rotated on the left side about the vertical axle. The oscillating motion is produced with an *intermittent mechanism*. Leonardo created a mangle by using two lantern pinions on the same vertical shaft and using a partially toothed crown-wheel gear rotating about the horizontal axis. The teeth on the vertical wheel first engage the double pinion at the bottom turning it in one direction, and then engage the upper lantern pinion turning it in the opposite direction. The sliding link attached to the double pinion moves the horizontal shaft back and forth. Finally the partially toothed crown wheel gear has another set of pin type teeth on its outer rim that are driven by a helical screw, called an endless screw or worm drive mechanism.

The machine elements in this machine as categorized by Franz Reuleaux include:

(i) journal and thrust bearings;
(ii) belts and pulleys;
(iii) toothed wheels (gears);
(iv) revolute and prismatic (sliding) joints;

(v) screw elements.

The kinematic mechanisms in this machine include:

(i) two belt drives;
(ii) a double slider linkage;
(iii) a mangle or intermittent mechanism;
(iv) an endless screw mechanism.

We do not know if Leonardo invented this design or whether he copied it from existing machines of the time. However, it is an interesting proposition that if one is given the need for such a machine and given a list of five machine elements and four mechanisms, could one create such a machine? How did Leonardo create such a machine if he did not copy it? Perhaps he saw a similar machine and was inspired to make improvements. He was trained as a painter and sculptor not an engineer. Or was it because as some have claimed, he was a genius.

Reuleaux believed that genius was not essential to creating a new machine; there was a rational process behind invention, though he had never quite discovered it. Reuleaux posited that a necessary condition for machine synthesis was knowledge of its basic language; machine elements and kinematic mechanisms. Leonardo da Vinci believed that there were rational principles to the art of painting based on mathematical proportions and perspective. There is now evidence that Leonardo had similar beliefs about invention of machines.

I.4 LEONARDO, 'INGÉNIEUR ORDINAIRE'

Was Leonardo an artist who dabbled in sketching machines or was he an engineer who painted in his off-hours? To place our discussion of Renaissance machine design and invention in context, we review the salient facts about the life and times of Leonardo da Vinci. There are literally hundreds of books on Leonardo as an artist, though there are less than a dozen paintings attributed to him. In this brief summary we review those aspects of his life related to his work as a royal engineer. There is often debate as to the facts and dates surrounding the life of Leonardo. Many of the dates given here are from the works of Kenneth Clark (1939, 1988), Ivor B. Hart (1961) and Charles Gibbs-Smith (1978).

Leonardo was born on April 15, 1452 in the village of Vinci northwest of Florence. His death is recorded as May 22, 1519 in Amboise, France. His was an out-of-wedlock birth whose father Ser Piero da Vinci was a notary and who acknowledged Leonardo's patronage and took him into his home. As a teenager, Leonardo was apprenticed into the workshop of the painter, sculptor and goldsmith, Andrea del Verrocchio [1435–1488] around 1470 where Sandro Botticelli was also a student. There he learned the skills of drawing, painting, sculpture and perhaps architecture. Leonardo later joined the Guild of St. Luke as a painter at the age of 20 while still living in Verrocchio's studio. Several biographers write that he likely had some formal education and studies in mathematics. However he did not receive study in Latin and tried to learn this language of science and literature later in life. Leonardo's Notebooks were written in Italian and he had considerable knowledge of geometry. His right to left writing was likely a consequence of his left-handedness and not an attempt to hide his knowledge as some have speculated.

From the age of 20 to 30 in Florence, Leonardo developed a reputation as a genius artist with creations such as the 'Ginevre de' Benci' (1474) now in the National Gallery in Washington DC, 'The Madonna and Child' (1476) in the Alte Pinakothek, Munich, and the 'The Benois Madonna' (1478–1480) now in the Hermitage, St. Petersburg. The definitive text on the paintings of Leonardo da Vinci is that of Kenneth Clark (1939). However this classic work does not discuss nor describe Leonardo's drawings of machines in Leonardo's Notebooks, not even from an artistic point of view.

The 15th century was a time of tremendous change and political tension, especially in the Italian states. Two of the most powerful rulers during Leonardo's years in Florence were Cosimo de' Medici [1389–1464] and Lorenzo de' Medici [1449–1492]. Under both rulers art, architecture and literature flourished. Under the reign of Cosimo, the architect-engineer, Filippo

Brunelleschi, completed the great octagonal dome (55 meters across) of the Cathedral of Florence in 1436. The movable-type printing press was invented by Gutenberg in 1450, and by 1500 there were nearly 300 printing press workshops in the Italian states. (This is important because Leonardo would have had an opportunity to disseminate his ideas and writings had he so chosen.) Florence was a center of silk and wool textile manufacturing, Italian mariners had taken a new class of sailing ships as far west as the Azores and later in 1492, Columbus would make the most fantastic voyage to the New World. Copernicus was born when Leonardo was 21. Politically however, times were very unstable. Constantinople fell to the Turks in 1453, and there was constant strife between the multifarious Italian states as well as interlopers such as the French and the German states that looked on this lack of unity as an opportunity to acquire new territory and hegemony. One can clearly understand the demand for military engineers by powerful regional rulers as well as for artists and sculptors.

At the age of 30 in 1481, Leonardo wrote a remarkable resume for the Duke of Milan, Ludovico Sforza [1452–1508], known also as 'il Moro'. A draft of this letter in his notebooks (CA Folio 1082r/Folio 391r.a), boasts of Leonardo's skills as a military and civil engineer and briefly mentions his considerable skills as a painter and sculptor at the end of this letter.

> Having, most illustrious sir, seen and considered the experiments of all those who profess to be masters in the art of invention of the apparatus of war and, having found that their instruments do not materially differ from those in general use, I venture, without wishing to injure anyone, to make known to your Excellency certain secrets of my own, briefly enumerated as follows;

Among the list of ten skills that Leonardo boasts to Il Moro are the following;

> 4. I know how to make light cannon of easy transport, capable of ejecting inflammable matter, the smoke from which would cause terror, destruction and confusion among the enemy.
> 7. I can make cannon, mortars and engines of fire, etc., of form both useful and beautiful and different from those at present in use.
> 10. In times of peace I believe that I can compete with anyone in architecture and in construction of both public and private monuments and in the building of canals.
> —; in painting I can do as well as anyone else.

This job description is not unlike that of a modern engineer, who is often employed in defense industries in times of real or threatened war. The other

interesting point is Leonardo's description of these engines of war as 'beautiful'. Engineers then and now often look at a new creation with a sense of beauty and awe, independent of the moral use of the new technology and Leonardo seems to be no different.

In 1482, Leonardo left for Milan and was appointed 'ducal painter and engineer'. He spent the next 18 years working for Il Moro, serving as consultant on fortifications at Milan, Pavia, and Vigevano. He completed his famous painting 'The Last Supper' in 1497. In 1498, he was given a vineyard property by his patron with the title *ingegnere camerale*. Leonardo stayed in the service of the Duke for 17 years. In 1499–1500, Ludovico Sforza was displaced by the French King Louis XII in his occupation of Milan, and Leonardo left for a brief stay in Venice in 1499 and later returned to Florence in 1500. In Venice he was occupied with some military consulting for the Venitian Senate. He also worked with the mathematician Pacioli who had fled with Leonardo from the troubles in Florence.

Besides undertaking some paintings, a great deal of Leonardo's service to 'Il Moro' was involved in surveying fortifications, devising town plans, drawing plans for canals, organizing pageants and providing advice on military technology. To carry out these tasks there are a number of names in his Notebooks of workers and students in his Milan workshop whose professions were machine makers, locksmiths and glass craftsmen suggesting that he was surrounded by men who had some experience and knowledge of machines and technical processes.

During his time in Milan, Leonardo traveled to Pavia in 1490 and met the older Francesco di Giorgio Martini [1439–1501] from Siena a respected artist-engineer who, following the work of another Sienese engineer Mariano Taccola, had published a widely circulated book with descriptions and drawings of machines for military and construction purposes. From a record of books in Leonardo's library, we know he had a copy of Francesco's book on architecture and machines. In fact most of Leonardo's own Notebook drawings of machines date from after this time (Table I.2).

Another important contact *vis-à-vis* his education as a machine designer and engineer, was his friendship with the mathematicians such as Fazio Cardano of the University of Pavia and Fra Luca Pacioli who later wrote on arithmetic and geometry. Leonardo drew the illustrations for Pacioli's book *De Divina Proportione* in 1509. The relation between mathematics and machines has its origins in the work of Aristotle, Hero, and Archimedes. The earlier picture books of Taccola, and Francesco di Giorgio however, did not show the precision that was necessary for machine construction until the work

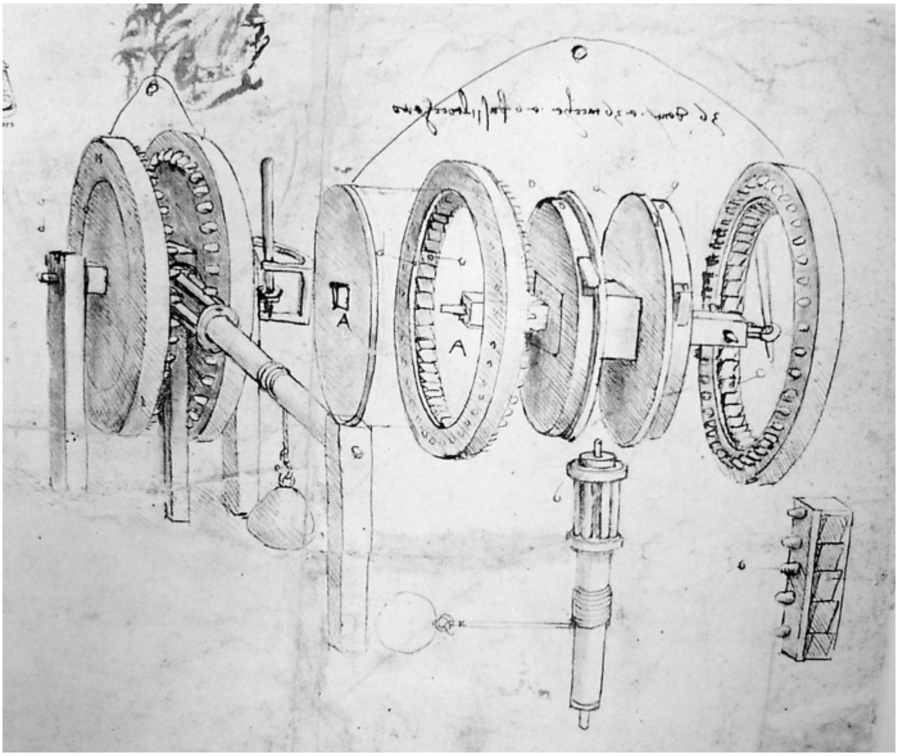

Figure I.16. Leonardo da Vinci: Exploded view of a ratchet winch (*Codex Atlanticus*, Folio 30v/8v.b)

of Leonardo whose interest in geometry is clearly visible in his machine drawings. Often one finds both geometric drawings and machine components drawn on the same page. His exploded views for some machines give one the confidence that one could reproduce these machines from his illustrations (Figure I.16). This emergence of careful attention to geometric and perspective details later appeared in the machine books of Besson (1578) and Ramelli (1588).

Leonardo's Notebooks contain many studies on the science of mechanics and dynamics. In later centuries, Galileo and Newton would focus such study on the motion of heavenly bodies. However the science of mechanics is also intimately connected to the design of machines. Leonardo spent considerable time on the subjects of equilibrium of forces, strength of materials, friction, elastic bodies and the bending of beams, cracks in solids, the motion of projectiles and a considerable effort on the motion of fluids or hydrodynamics. The subject of mechanics is highly relevant to the design of machines such as

in the problem of bearings to reduce friction, and in the design of pumps to move water or the construction of large flexible crossbows. Leonardo's troika of interest in geometry, mechanics and machines was the beginning of the scientific codification of engineering design, a process that continued to the end of the 19th century and the work of the engineer-scientist Franz Reuleaux. Of the study of mechanics Leonardo would write in his Notebooks (Ms E 8v) this oft quoted aphorism: '*Mechanics is the paradise of the mathematical sciences because by means of it one comes to the fruits of mathematics*'.

In 1500, Louis XII of France occupied Milan and Leonardo left for Venice and Florence and then a tour of duty in Rome with Cesare Borgia, Duke of Romagna. During this time Leonardo produced maps for the construction of canals, another engineering task that involved careful geometric drawing skills. In the 20 years after he had left Florence he had started a number of paintings and sculpture projects, but very few were ever finished or survived. Shortly after the Milan period, Leonardo completed his famous Mona Lisa, completed in 1503, now in the Louvre in Paris. In 1506, Leonardo returned to Milan for a few months. The French who were still in Milan referred to Leonardo as '*nostre peintre et ingénieur ordinaire*'. He also spent a short time in Rome from 1514–1516, but was overshadowed artistically by the younger Michelangelo and Raphael.

In the post Milan period 1507–1509 Leonardo took a stronger interest in scientific studies especially those involving anatomy, hydrodynamics of water and the flight of birds including the design of flying machines. One of his notebooks of 30 pages is entitled *Codice Sul Volo degli Uccelli* (1505) or 'On the Flight of Birds'. Some of these wing-like devices exhibit cable and linkage designs similar to those that appeared centuries later in the work of Otto Lilienthal, who was a student of Franz Reuleaux at the Berlin Polytechnique.

Finally like a man without a country, in 1516–1517 Leonardo received an offer to reside in the palace of the French King Francis I at Chambois, where he received an appointment as '*Premier peintre et ingénieur et architecte du roi*'. Here Leonardo lived in an 'emertius' status, a royal trophy artist, often conversing with the King but with few duties. Leonardo died in 1519 at the age of 67 and was buried at the Church of St Florentin, Amboise.

Although Leonardo made thousands of drawings, sketches, designs and pages of notes on dozens of subjects, we have no record of a published book. There is some historical reference to a book on principles of painting. But in engineering, he did not write or publish any book on the subject for which he later gained universal respect, the design and invention of machines. His drawings, papers and notebooks were bequeathed to a younger

pupil, Francesco Melzi [-d. 1570] who kept them until his death at which time Melzi's son mishandled them. These papers were later given to the sculptor Pompeo Leoni who tried to reorganize the welter of drawings into codices related to several themes. In this work he often cut out drawings and pasted them into other works. The largest collection of manuscript pages was called the *Codex Atlanticus*, over 1000 folios, and was given to the Biblioteca Ambrosiana, Milan. This large twelve-volume work contains hundreds of machine drawings. This work was first published in facsimile in 1894 and can been found in many large libraries around the world. A compressed three-volume version has recently been published in Italian in 2000.

Another codex is in Windsor, England as well as a few smaller books at the Victorian and Albert, in London. There was a set of 13 smaller notebooks labeled A–K that were looted in Milan by Napoleon's troops in 1796 and now reside at the Institut de France in Paris. Several of these books, namely *Manuscripts B*, *G*, and *H* contain machine drawings. The other major books were in the National Library Madrid, Spain but were 'lost' in the 19th century due to misfiling. In 1965, the *Codex Madrid I and II* was found and were translated and reproduced in facsimile. These works contain over a 1000 important drawings of so-called *machine elements*, the basic building blocks of all machines.

The late da Vinci scholar, Ladislao Reti, in the process of translating the newly discovered *Codex Madrid*, made a very important observation that is summarized in Table I.3; that Leonardo's drawings of elements of machines correlated with a list of such machine elements compiled by Franz Reuleaux in the late 19th century.

In 1938, Edward MacCurdy published a translation of many of the text sections in the Leonardo's Notebooks. These quotations reveal the extent of his self-education and readings. In different codices Leonardo mentioned the Roman engineer Vitruvius, Archimedes, the Commentaries of Caesar, or the geometry of Euclid. In a remarkable discovery in the recently translated *Codex Madrid II*, was a list of "*books I have left locked in a chest*". This list of over 100 books includes works on Aristotle, The Bible in Italian, Letters of Ovid, St Augustine, Justinius-Roman historian, Fables of Aesop, Petrarch and Pliny. In mathematics, he had books by Euclid and Luca Pacioli. In architecture and engineering his library contained books by Alberti, Valturio and Francesco di Giorgio as well as one entitled 'A Book of Engines'. There is also one likely to be Philon of Byzantium's 'Pneumatics'. It is interesting to note that although the Roman engineer Vitruvius is mentioned by Leonardo in several locations in his manuscripts, his work is not listed in the book list

Table I.3. Reti's comparison of Leonardo's and Reuleaux's basic machine elements

Reuleaux's 'Constructive Elements' in *Kinematics of Machinery*, 1876	Leonardo's 'Elementi macchinali'	*Codex Madrid I*
Screws	Section 107	Folio 26r
Keys	Section 108	Folio 46v
Rivets	Section 109	—
Bearings	Section 112	Folio 101r
Pins, Axles and Shafts	Section 110	Folio 10v
Couplings	Section 111	Folio 62r
Ropes, Belts and Chains	Section 113	Folios 9r, 23r, 10r
Friction Wheels	Section 114	Folio 102r
Toothed Wheels	Section 115	Folio 15v
Flywheels	Section 116	Folio 35r
Levers, Connecting Rods	Section 117	Folio 1r
Click Wheels	Section 119	Folio 117r
Ratchets	Section 121	Folio 12r
Brakes	Section 122	Folio 10r
Engaging & Disengaging Gear	Section 123	Folio 2r
Pipes	Section 125	Folio 25v
Pump Cylinders, Pistons	Section 125	Folio 5r-b (*Cod. Atlanticus*)
Valves	Section 126	Folio 115r
Springs	Section 127	Folio 85r
Cranks and Rods	Section 117	Folio 28v
Cams	Section 145	Folio 6v
Pulleys	Section 158	Folio 155r

in *Codex Madrid II*. Vitruvius's Book X of his treatise on Architecture was a key reference to machine engineering of Roman and Greek antiquity.

Compared to today's students of engineering and science, Leonardo had a wide knowledge of the liberal arts. He certainly did not fit the modern stereotype of the narrow technologist or what is today called a 'nerd'. Leonardo was widely read and cosmopolitan in his interests as well as widely traveled, which also characterized the 19th century engineer-scientist Franz Reuleaux whose life we describe at the other end of the four centuries of the evolution of the machine.

Influence Network of Leonardo da Vinci in Machine Design

Leonardo da Vinci is sometimes portrayed in contemporary media as a singular genius especially in the subject of machines and inventions. However as there were artistic influences of earlier painters and sculptors on Leonardo's art, there were also earlier architect-engineers and artist-engineers who were either building or drawing designs for machines and whose work likely had some influence on Leonardo.

One of the popular methods to graphically summarize the evolutionary influences of ideas in machine design and invention on Leonardo da Vinci is with an influence network chart shown in Figure I.17. A similar chart was made by Ladislao Reti for the work of Francesco di Giorgio (see Figure II.33 in Part II of this book), as well as the chart for Franz Reuleaux in the following section. In this chart, time flows from left to right. On the left representing antiquity, we have the work of Archimedes, Ctesibius and Hero of the Greek Alexandrian School summarized by the Roman architect-engineer Vitruvius around 27 CE. These works are cited as influencing Leonardo because the work of Vitruvius was rediscovered in the 15th century and Francesco di Giorgio attempted a translation himself. There is also the influence of thinkers such as Roger Bacon and scholars in mathematics and mechanics in the late Middle Ages such as Villard Honnecourt or perhaps the Arab writer al-Jazari, but the direct links to the Renaissance engineers is not clear. Another engineer of record is Guido de Vigevano (1335).

What is clear is the influence of Filippo Brunelleschi and his chroniclers such as Ghiberti and Sangallo, who made drawings of many of his construction machines (see e.g. E. Battisti, 1981, 2002, pp. 132–136; P. Galluzzi, 1997, pp. 93–116). Another established line of influence is that of Mariano Taccola and Francesco di Giorgio Martini. Since Leonardo had a copy of di Giorgio's work in his library, a direct connection between Leonardo and Francesco di Giorgio seems appropriate. I have shown a solid arrow to indicate that Leonardo had copies of the works of other nodes of the chart, such as Leon Batista Alberti, Roberto Valturio, and Bonaccorso Ghiberti. Dashed lines indicate probable influence on Leonardo's machine work, such as that of Giuliano da Sangallo. Earlier machine catalogs of the late 14th century such as those by Giacomo Fontana and Konrad Kyeser (c. 1405) are likely to have influenced 15th century engineers but the direct evidence is not clear.

The influence lines of Leonardo himself on other contemporary and later nodes are more problematic since his manuscripts were never published. However some scholars, such as Ivor Hart (1961) believe that the executor of the manuscripts after Leonardo's death in 1519, Francesco Melzi, may

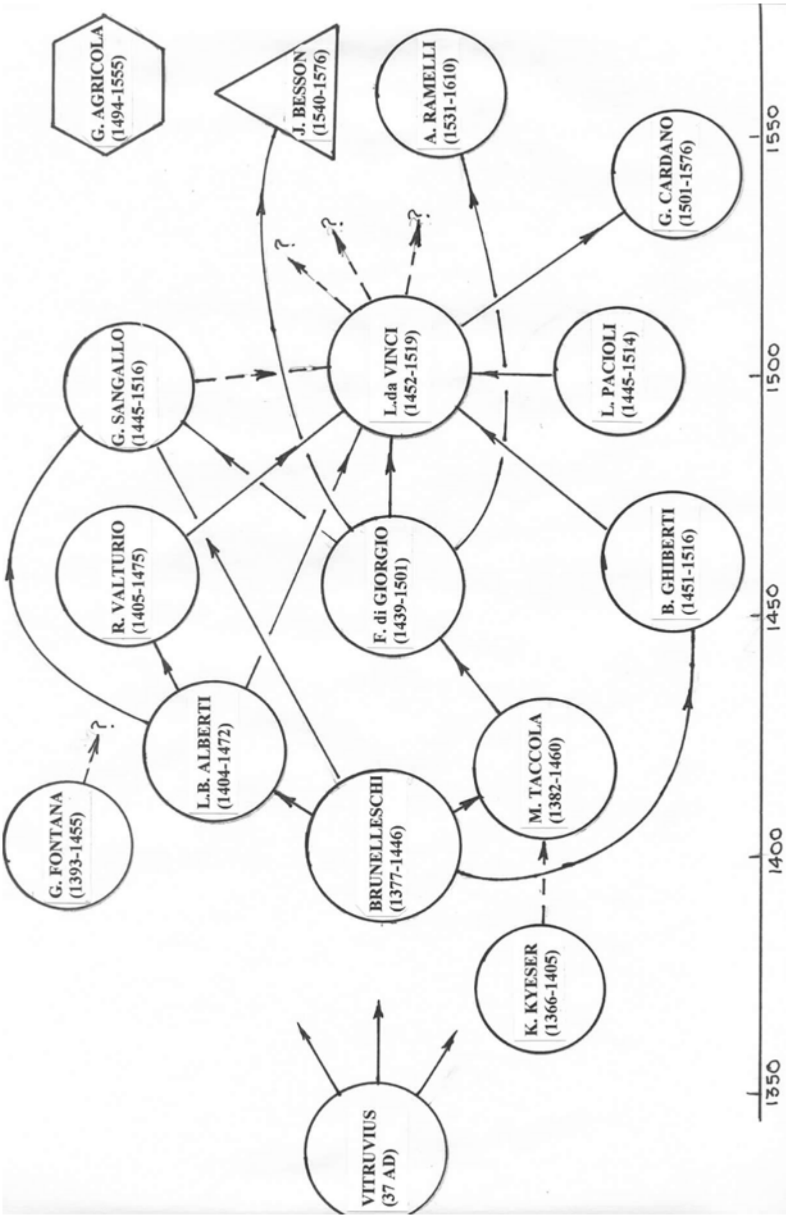

Figure I.17. Influence network of Leonardo da Vinci

have allowed certain artists to make copies from the manuscripts or allowed scientists and scholars to read some of the manuscripts in the half century period that Melzi had them in his possession. Two possible lines of influence of Leonardo are Fazio Cardano [1444–1524] and his son Girolamo (Jerome) Cardano [1501–1576]. The latter became a famous mathematician and is credited by Reuleaux as having described the famous kinematic mechanism for transmitting rotary motion from non-aligned shafts called the *Universal Joint*.

Within the half century period of Melzi's caretaking were published important machine books of the Italian Agostini Ramelli (1588) and Besson (1578) in France. The machine book on mining by the German, Georgius Agricola (1556) was also published in this period as was one on metallurgy by Biringuccio (1540). (See Section II.9, for a discussion of the so-called 'theatre of machines books' of the 14th through 18th centuries.) According to Gille (1966) other technology books on agriculture, chemistry and arms appeared in 16th century after Leonardo's death by authors from what is now England, Spain, Germany and Italy. This plethora of knowledge books on engineering and technology was one of the hallmarks of the Renaissance machine age.

One can debate the details about direct or indirect influence on and by Leonardo's work in machines and mechanics. However the overall features of the influence chart in Figure I.17 support the premise of this book and earlier works, that workshop knowledge of machine creation evolved over several centuries, especially during the Renaissance.

I.5 FRANZ REULEAUX: ENGINEER-SCIENTIST

The Age of Machines in the 19th century had many well-known personalities such as Siemens and Otto in Germany, Watt and Brunel in England, and Fulton and Edison in the United States. When a lesser-known figure such as Franz Reuleaux is studied, it is natural to compare him with the more famous men of the industrial revolution. However in his day, Franz Reuleaux [1829–1905], was very well known for his theories in machine design and was a player on the stage of new technologies. He was a principal consultant to Otto and Langen on the gas combustion engine as well as a friend of Siemens. He was ambassador to international expositions, a proponent of German educational theories and an advocate for machine style and art in the industrial age. He was such a cosmopolitan personality that he garnered recognition and honors around the world, was referenced in dozens of books and papers and memorialized in Berlin with a monument and a named street, yet was forgotten by the end of the 20th century. Reuleaux was not an inventor like James Watt, or an entrepreneur like Werner Siemens, nor was he a scientist like Faraday or Henry. Yet he played a crucial part in the later stages of the 19th century machine age, the role of engineer-scientist, professor, university head, advisor to industry and government.

One way to begin to understand a historical figure like Reuleaux is to paint a portrait of him through his words and images. Picture a bearded man with a large head, high forehead, deep set eyes, receding hairline, dark wavy hair swept back over large ears to just below his collar. His pictures show a hand tied cravat and a vest or waistcoat under a frockcoat. His letter books contain copies of thousands of letters in German, French and English written in a flowing pen with a bold finish of his name *Reuleaux*. These letters are addressed to colleagues, students, and industrialists in a formal, gracious, courtly style that one often associates with the Victorian age. There is one picture of Reuleaux standing next to his desk in a silk lapelled morning coat that suggests he was no more than one meter and two-thirds in height, or about five feet five inches. Yet his photographs convey an imposing personality.

If Leonardo's fame as an artist overshadowed his life as an engineer and scientist, in the case of Franz Reuleaux, his practical books on machine design have overshadowed his interest in a theory of invention and creativity in mechanical artifacts.

> In each new age of intellectual creation, the inventor works as does the artist. His genius steps lightly over the airy masonry of reasoning—It is useless to demand of the artist or inventor an account of his steps. (Reuleaux, 1876a, p. 6)

At the same time Reuleaux recognized the new role of science and mathematics in developing a rational method of machine design. In speaking about the industrial progress of the 19th century he remarked that

> The forces of nature which that advance taught us to look for – are mechanical, physical and chemical; but the prerequisite to their utilization was a full [employment] of mathematical and natural sciences. (Reuleaux, 1885, p. 7)

Short biographies and obituaries written about Franz Reuleaux are laudatory and respectful, in awe of his accomplishments. Though he had many admirers, he also had strong critics. One does not play a leading role in the development of engineering at the Zurich Polytechnique, sit on the German patent board, head the Berlin Industrial Academy for 12 years and play an important role at the Royal Technical University in Berlin without making political enemies.

Reuleaux's family had Belgian roots in the 18th century as pump makers and hydraulic engineers in a village near Liege. Later in the early 19th century the family moved to a village outside of Aachen called Eschweiller-Pumpe. After the fall of Napoleon in 1814, Aachen or Aix la Chapelle was ceded to Prussia and later became absorbed into Bismarck's united Germany after the German-Franco war in 1867. Franz's father was one of the first manufacturers of steam engine pumps in Belgium and Germany. Franz was born in 1829. His father died in 1833 before he was five and the family moved to Koblenz where one of his uncles continued the family business. Living in the Rhine Valley, it was perhaps natural that the young Reuleaux would attend the Karlsruhe Polytechnique Institute [1850–1852] to study machine engineering with the then famous Ferdinand Redtenbacher. After two years Reuleaux went to Berlin to study philosophy and the natural sciences and then to Bonn to continue studies. Returning to the Rhine Valley, he worked in the family business building machines. He also worked at a mechanical institute in Cologne. In 1856 at age 27 he was invited to become professor of mechanical engineering at the Zurich Polytechnique Institute, now known as the Swiss Federal Technical University, or ETH (Eidgenössische Technische Hochschule).

In 1864 he began his leadership positions in Berlin, where he would spend the rest of his career first as director of the Gewerbeakademie (1868–1879) and then as rector (1890–1891) of the combined Gewerbeakademie and the Bauakademie, that formed the Technische Hochschule Berlin. At TH Berlin, Reuleaux was the director of mechanical engineering. He also held the title,

Royal Privy Councilor, and served as a consultant to the new German Reich. Reuleaux was a member of the Imperial Patent Office for eight years.

Reuleaux's father Johannes Joseph was born in Eschweiller-Pumpe in 1796. Records indicate he was baptized a Catholic. He is listed in records as a 'Mechanikus und Fabrikant' Reuleaux's mother, Walburga Carolina Heloisa Graeser [1803–1867] also from Eschweiller was baptized Evangelical or Lutheran as called in the US. His mother was a writer of children's books and novels for young girls under a pen name 'Die Grossmutter'. Reuleaux's parents had five boys and two girls. One of Franz's sisters died in 1832, age 13 months, and a younger brother died shortly after the death of his father at age 8 months. Of his three older brothers, two became engineers. One brother, Ludwig (Louis in some records) is recorded as a manufacturer or 'Fabrikant'. Later in life he became head of the Mainz Trade Council. Because his father died when Franz was age six, it is likely that Franz was influenced more by his uncle and older brothers, than by his father. Also, his mother, who later moved with Franz and his wife to Berlin, may have encouraged his interest in art and literature (see Zopke, 1896 and Seiflow, 1999).

Reuleaux married Charlotte Overbeck [1829–1908] of Antwerp, Belgium. They had three girls and two boys – Caecilie [1857], Mathilde [1859], Else [1869] who died at age four. One son Oscar [1861–1920], had the title Major in references, while the younger son Eugen, born in 1866, went to the US in 1894. There are genealogical records that trace his family to Canada and Wyoming. There is a copy of a letter of Reuleaux to a manufacturer in the US seeking a job for his son. Although Reuleaux traveled all over the world in his professional life, there are no references in his letters we have seen that his wife ever traveled with him.

Franz Reuleaux was a collector. He not only built a collection of 800 models of machine mechanisms in Berlin, at home he collected spindles used by primitive and non-industrial societies to spin thread. A rare photo of him in his office at home shows him attending to this collection. The darkly paneled Victorian decorated room also shows a collection of vases on shelves below the ceiling. Letters of Reuleaux to the Smithsonian Institute in Washington DC contain references to stuffed animal heads that he wanted sent to him in Berlin. He was also interested in anthropological artifacts during his trips to Australia and India. Reuleaux was president of the Berlin Art Dealers Association for several years and was appointed by the Kaiser to purchase art for a museum in Berlin.

His penchant for collecting reached its pinnacle with his vast kinematic model collection in Berlin. Even here, many models were of mechanisms

that had origins in antiquity such as the endless screw or the verge and foliot clock escapement of the late Middle Ages. Reuleaux believed that understanding machines of the past had lessons for contemporary design; '*the thorough understanding of old mechanisms is even more important than the creation of new ones*' (Reuleaux, 1876a, p. 21).

After leaving Karlsruhe, Reuleaux published a handbook on machine design in 1854 with a fellow student Carl L. Moll. Their former Professor Redtenbacher from Karlsruhe however was not happy and accused his former students of publishing his class notes. Later Reuleaux published the first edition of his popular machine design text *Der Constructeur* in 1861. This work went to four editions and four languages, including an English edition in 1893. This work contains descriptions of many different types of machines as well as machine components (Table I.4). The first editions of this work had very little kinematics of machines. Reuleaux's German text *Theoretische Kinematik* appeared in 1875 and was quickly translated into English in 1876 as *The Kinematics of Machinery: Outlines of a Theory of Machines*. A second volume appeared in German in 1900.

Besides his prolific technical writing, Reuleaux wrote a controversial book on his visit to the 1876 Centennial Exposition in Philadelphia, called *Briefe aus Philadelphia*. He also wrote a book on his travels to India in 1881, (*Eine Reisse Quer durch Indien*) complete with numerous lithographs of the people and sights there. During his visit to the Chicago Columbian Exposition in 1893, Reuleaux was inspired to translate Hawthorne's poem 'Hiawatha' into German. As a result of his second visit to America, he wrote a report on American machine industry (*Mittheilungen amerikanische Maschinen-Industrie*). A truly remarkable achievement is his editorship of a nine volume series of books on inventions, called *Buch der Erfindungen*, in the 1890s. What is special about this encyclopedic work are the nearly 1000 lithographs that show not only machines and industrial processes but also hundreds of pictures showing workers and machines including many of women involved with technology and in the factories.

Reuleaux also had concerns about the impact of technology on society and the disparity between the nations with technology and those who are without. In a speech in the 1880s titled, 'Cultur und Technik' later translated into English in 1885 and published by the Smithsonian Institution, he posed this enigma:

> – a full two thousand years ago,– Indian poets had produced their nation's Odyssey, the Mahabharata, and dramas in rich abundance. – Philosophy flourished – Mathematics too was fostered. – Where

Table I.4. Selection of machines cited in Franz Reuleaux's *The Constructor*; 4th Edn(1893)

Manufacturing Machines	**Page**	**Construction Machines**	**Page**
Cotton-spinning machinery	124	Cranes	27, 38, 89
Seller's engine lathes	126	Bridge roller bearings	126
Seller's planing machine	140	Hoisting machinery	156
Wine press	154, 241	Chinese windlass	174
Saw mill feed mechanism	160	Pumps: Pappenheim, Payton, etc.	219, 220
Jacquard loom-ratchet gearing	163	Archimedes screw pump	221
Eckert threshing mill	186	Franklin's double pump	224
Jacob's grinding mill	187	Canal locks	227
Hydraulic riveting machine	228	Hydraulic ram	233
Sand blast machines	241	Worthington duplex pump	231, 232
Electro-plating machines	241		
Nasmyth steam hammer valve	286	**Power and Transmission**	
		Steam engines	110
Military Machines		Steam engine flywheels	143
Gun locks; releasing ratchets	162	Corliss steam engine valve gears	162
Mauser revolver; locking ratchet	166	Dynamo-electric machines	171
		Hot-air engines	171
Transportation Machines		Hydraulic piston and cylinder	216
Wagon wheel suspension springs	20	Compressed air distribution	219
Locomotive Wheels	125	Water turbine wheels-Borda	220
Stephenson's locomotive valve gear	143	Screw turbine, Cadiat's turbine	220
Railroad brakes	164	Windmills	220
Westinghouse railroad air brakes	171	Hornblower compound engine	234
San Francisco cable tramway	174	Vacuum pump valve gear	236
Atmospheric railway of Pinkus, 1834	227	Riedler pumping engine	278
Hydraulic ship steering gear	237	Gas main gate valving	282
Davies steering gear	238		
Locomotive boilers	271	**Measurement & Communication**	
		Thomas Calculating machine	153, 156
		Morse telegraph	163
		Thomson telegraph	164
		Clock escapements, Le Roy, Arnold	167, 168
		Recording telegraph	171

> then, is the difference in intellectual sphere which has allowed a separation between them and us? – Let us ask, whence is the source of our material preponderance over them? How, for example, has it become possible that England, with a few thousands of her troops, should rule supreme over a quarter of a milliard [*sic*] of the natives of India. (Reuleaux, 1885, p. 3)

Reuleaux went on to argue for an education system based on science. This and other writings, shows his interest in societal questions beyond his technical studies.

What is also amazing about Reuleaux is that these books and writings were accomplished throughout a period from Zurich in 1856 to Berlin 1896 when he was either head of a department, institute or president of a university, along with his royal appointments in the patent office and as industrial consultant.

How can we compare Franz Reuleaux with Leonardo da Vinci? Both grew up in a workshop tradition but attempted to generate principles of machine invention and design later in life. Both were engineering advisors to government and royalty. They each communicated with many creative and influential people of their day. Though Reuleaux was never a professional artist like Leonardo, he loved to draw and illustrate his books with hundreds of drawings. In spite of their love of machines, neither became a producer of machines though Reuleaux did reproduce his small kinematic models for universities. Their differences are also important. Leonardo never received a formal education. Reuleaux married and had a family. Both Leonardo and Reuleaux were famous in their day; yet at the end of their lives, each had suffered a loss of influence. Perhaps their most unifying trait was their love of machines and the belief that the invention of mechanical devices was a wonderful gift to those who could master this art.

'Father' of Kinematics of Machines

Unlike James Watt, who was an instrument maker and craftsman, Reuleaux and his fellow engineer-scientists were trained in science and mathematics, philosophy and literature as well as in 'mechanical arts', influenced in part by the French 'Polytechnique' tradition with its strong emphasis on mathematics and mechanics. Unlike the craftsman-engineer who believed in trial and error, hands on education, the engineer- scientist believed that machines could be created and designed using scientific principles guided by rigorous mathematics.

Reuleaux is remembered today as one of the principal founders of modern kinematics of machines. *Kinematics* is the study of *pure motion* in machines without reference to forces. Classical theory of machines had roots in the Greek and Roman description of *simple machines*; the lever, wedge, screw, pulley and wheel. The focus of this ancient theory of machines was not on motions, but on overcoming large forces. This was a time when animal and human labor were principal sources of energy. By the end of the 18th century, the steam engine was more than a half a century old and French thinkers redefined the machine as a device that transformed *motions* as well as forces. Reuleaux's theory portrayed the machine as a chain of geometric constraints between kinematic pairs in which the motion of one link determined the motion of the rest of the parts.

Reuleaux also stressed the importance of *synthesis* in design and the use of topological concepts to enumerate a class of machine elements. In particular he advanced the use of the concept of pure rolling or *centrodes* for description of relative motion between machine parts. He developed methods of *kinematic synthesis* based on this idea of equivalent rolling between moving parts. Reuleaux also clearly enumerated a basic set of '*constructive elements*' in machine design that was largely copied in 20th century texts on machine design. Combining his technical and artistic interests, he espoused an aesthetic in machine design analogous to the optimum design of structures: namely that *an aesthetically pleasing shape in a machine structure will lead to an efficient use of materials*.

Reuleaux believed in the use of demonstration models to express mathematical and kinematic ideas. He built a large collection of 800 mechanism models in Berlin and marketed 350 of them to universities around the world. Unfortunately much of this collection was destroyed during World War II, but some originals and reproductions of these models can be found in the Deutsches Museum in Munich, the University of Hannover, Kyoto University, the technical university in Porto, Portugal, the technical university of Moscow and at Cornell University in Ithaca, New York which has the largest known collection of 230 models. (See Table II.5, Section II.13 for a list of international collections kinematic models.)

Franz Reuleaux's major work in kinematics was first published as a series of articles by the Prussian Society for the Advancement of Industry in 1871–1874 and published as a book in 1875 under the title, *Theoretische Kinematik: Grundzüge eine Theorie des Maschinenwesen*. It was translated almost immediately into English by Professor Alexander B.W. Kennedy of University College London in 1876 under the title, *The Kinematics of Ma-*

chinery: Outlines of a Theory of Machines. It was also translated into French and Italian, such was its impact on the engineering community in Europe. The ideas that Reuleaux presented in this book influenced the field of machine design for a century. A graphical summary of Reuleaux's influence is shown in Figure I.18. His theory of machines was seen as genius by many of his contemporaries and early generations of kinematics theorists into the 20th century.

Reuleaux introduced his *symbol notation*, a language of machines, which extended the ideas of Charles Babbage, one of the pioneers of computer science. His sequence of kinematic constraints in a mechanism became a sequence of symbols, each representing a unique geometric constraint. Thus a mechanism became a 'word' and a complex machine a connected sequence of symbols, i.e. a sentence of 'words'.

Reuleaux's principal philosophical question in his theory of machines was; how did the machine and its mechanisms come into the mind of the inventor? In the Introduction to his book he wrote,

> What is left unanswered is however the other, immensely deeper part of the problem, the question: How did the mechanism, or the elements of which it is composed originate? What laws govern its building up? Is it indeed formed according to any laws whatsoever?

To this question Reuleaux quoted Newton and Göethe and commented that both the machine inventor and the artist must use similar mental processes; "*art and science flourish together in the same soil*". Reuleaux believed that there were logical processes to machine invention and that his ideas of kinematic chains of element pairs and topological expansion of a class of mechanisms were key tools in this logical process. "*I believe I have shown, —, that a more or less logical process of thought is included in every invention*".

In addition to having major industrialists such as Siemens and Langen as friends, Reuleaux produced some famous students such as Lilienthal of glider fame, Mannesman, Linde and Junkers who later became a major airplane producer. Reuleaux can also take some credit for driving a student to fame outside of engineering, namely the American photographer Alfred Stieglitz. Sent by his New York father to study mechanical engineering with the famous Berlin engineer, Stieglitz found Reuleaux's lectures so boring and that he quit engineering and took up the study of photography.

Franz Reuleaux was one of the optimists of the machine age who believed in the power of technology to free mankind from the slavery and prejudices of peasant life, in spite of the terrible toll on the industrial worker. In his time, machines were viewed with awe and marvel. He and his generation saw the

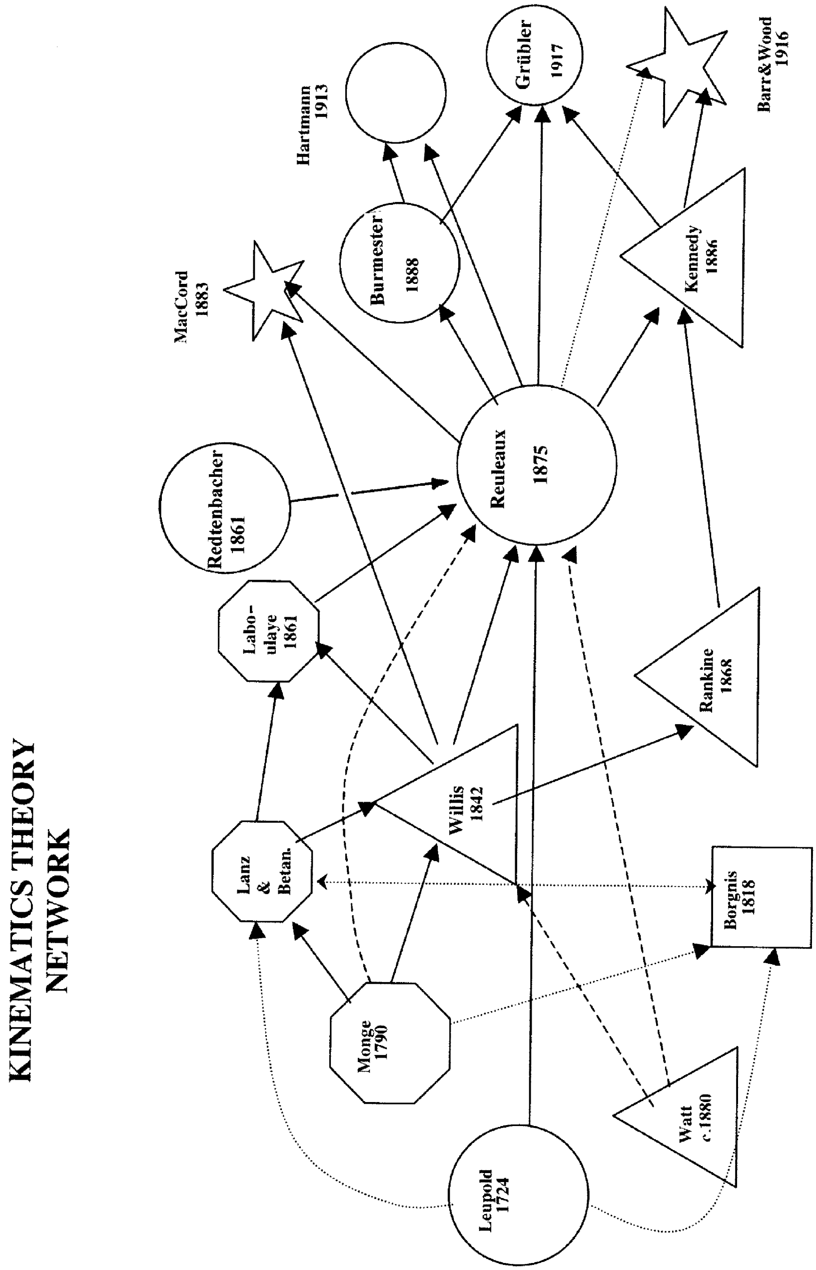

Figure I.18. Influence network of Franz Reuleaux in the 19th century related to the kinematics theory of machines

Age of the Machine as a continuity of progress reaching back to the Greeks and Egyptians as part of the destiny of humankind. Machines were the embodiment of man's knowledge and control over nature. He viewed the evolution in the development of the machine as an analog to the development of advanced societies in which education, crafts, manufacture and government are linked in a chain of mutual dependency for the common good (Reuleaux, 1885).

Reuleaux's life spanned the period of enormous growth in travel spurred by the development of powerful steam engines that carried people across oceans and continents by steamship and railroad. He traveled to World Exhibitions in London (1862), Paris (1867), Vienna (1873), Philadelphia (1876), Sidney (1879), Melbourne (1881) and Chicago (1893), often as German ambassador to these fairs. His professional life coincided with new communications such as overseas mail and the telegraph that linked the growing industrial world with the first Internet.

Reuleaux was a player in the political world of the machine age. One of his most famous roles was as the German ambassador to the Centennial Exhibition in Philadelphia in 1876. In his official duties at Philadelphia he sat on judging panels and wrote articles on industrial advances exhibited at the Exposition. These articles were published in Berlin newspapers and appeared as a book, *Briefe aus Philadelphia* (1877) or 'Letters from Philadelphia'. He called the German manufactured goods at the Fair 'cheap and shoddy' (*billig und schlecht*) compared to British and American manufacturing. In this book he proposed an economic design principle; *when faced with competition, one should raise the quality, not lower the price*. Though he faced criticism for his remarks at home, this principle later became a hallmark of German manufacturing. Later at the 1893 Columbian Exposition in Chicago, Reuleaux was questioned by reporters from several technical magazines as to whether German manufacturers had improved over his 'billig und schlecht' description of 1876. He proudly responded that German goods were quite good but that the Americans had continued a lead in precision manufacturing, to which he was widely quoted in the American press and again criticized at home.

As mentioned above, Reuleaux believed there were scientific principles behind invention and the creation of new machines or what we call *synthesis* today. He attempted to posit principles of *design theory*, a subject that has come into vogue a century later. This belief in the primacy of scientific principles in the theory and design of machines became the hallmark of his worldwide reputation particularly in the subject of machine kinematics. His views also gained him critics, who believed he had placed too much empha-

sis on theory and not enough on engineering practice. After his death these critics tried to reverse the educational structure Reuleaux had helped to build in German engineering institutions.

In recent decades there has been increasing interest in artificial intelligence, synthesis and creativity. Reuleaux's works contain many early ideas about machine invention and synthesis, machine aesthetics, design principles, modular elements as well as best practice rules for design. He viewed his kinematic ideas as prefatory to a theory of scientific invention of machines. He also referred to "*general laws of invention*". He compared creative thinking to the motion of links in a machine, a process governed by logical rules.

> Essentially invention is nothing less than induction, a continually setting down and therefore analyzing of the possible solutions which present themselves by analogy. The process continues until some more or less distant goal is reached. (*Kinematics of Machinery*, 1876, p. 52)

Reuleaux's general interest in the history of invention is exhibited in an eight volume series that he served as editor, *The Book of Inventions* (*Buch der Erfindungen*) a pictorial, popular book on the history of invention from the early Egyptians to the end of the 19th century (Reuleaux, 1884). He did not accept the contemporary theory of invention as resulting from scientific discovery, a view that is often expressed in popular literature on technology in the United States. Nor did he believe in the discontinuous genius theory of invention, where the 'hero' inventor, working alone, makes an important advance that benefits humankind. He viewed both scientific discovery and technical invention as evolving from a tension between the two, sometimes within the same man. Reuleaux viewed the development of new machine technology as one of *evolution*, that every invention has had a close antecedent developed further by clever inventors, new scientific ideas and the pressure of marketplace competition. These ideas have appeared anew in recent books on history of technology and technical creativity.

Both Leonardo da Vinci and Franz Reuleaux spent a substantial part of their careers in the study of machines. There are some quotes in da Vinci's notebooks that speak of his passion for invention. But given his wide interests from painting to optics to anatomy we do not really know if he had a passion for machine design or whether he looked on engineering as simply a means to earn funds so he could devote time to his other scientific and artistic interests. Certainly some authors of books on Leonardo tend to draw that conclusion.

For Reuleaux, who himself had interests in art and anthropology, the study of machines was a passion for him. A few quotations of Reuleaux illustrate his 19th century philosophic and romantic view of The Machine. In describing the consequences of the idea that all relative motions of machine elements can be reduced to rolling, he wrote: "*the machine becomes instinct with a life of its own through the rolling geometric forms everywhere connected with it*, – mechanisms carry on "*the noiseless life-work of rolling*", – "*they are as it were the soul of the machine ruling its utterances – the bodily motions themselves – and giving them intelligible expression. They form the geometric abstraction of the machine*".

On Franz Reuleaux's death in 1905 at the age of 75, the American Machinist, published in both New York and London wrote a lead column in its September 14th issue:

> By the death of Prof. Dr. Reuleaux the engineering world loses one of its truly great men. Not merely was Prof. Reuleaux great in the sense of being an expounder of mechanical science and a teacher of it, but along with and above that he was a man of singular nobility of purpose and was actuated by the broadest and highest conception of his duty to himself and mankind. – The benefit to mankind resulting from the life and work of Prof. Reuleaux is simply incalculable: his reward is in a modest competence and an undying fame. Many a Wall Street operator, gambling in the things produced by aid of Prof. Reuleaux's work makes more money in a day that Prof. Reuleaux accumulated in a lifetime. — To many engineers in the United States he was a warm friend and by all was accepted as an exponent of what he himself called the union of science and practice in the art of the mechanical engineer.

I.6 INFLUENCE OF LEONARDO DA VINCI ON 19TH C. MACHINE THEORISTS

Did Leonardo da Vinci influence engineers and inventors in the 19th century Age of Machines? Did other Renaissance machine engineers such as Francesco di Giorgio Martini have any impact on machine design in the industrial age? For nearly three centuries Leonardo's manuscripts were in private and royal libraries. His thousands of separate folios were sorted and resorted, cut and pasted into several Codices now housed in Milan, Paris, Madrid, London and several other locations including Bill Gates home in Washington State, USA. However, the principal manuscript collections that pertain to machines and mechanisms are the *Codex Atlanticus* in the Biblioteca Ambrosiana in Milan, the *Codex Madrid* in the National Library Madrid, Spain, and the *Manuscripts A–M* in the library of the Institut de France in Paris.

Construction of machines in the early 19th century industrial revolution was primarily carried out in guild-like workshops, not too much different from that of the Renaissance workshops. These workshops were often run as a partnership of an inventor and entrepreneur as in the case of James Watt and Matthew Boulton in their building of steam engines in the late 18th century or Nicolas Otto and Eugen Langen and their internal combustion machines three quarters of a century later. The historical record shows that most inventors had little or no formal training in the sciences or technology, but as a group had a keen interest in new scientific ideas. For example, in a new book on James Watt and his contemporaries (Uglow, 2002), Watt is said to have learned German in order to read the *Theatrum Machinarum Generale* of Leupold (1724). Some of Leupold's drawings are very similar to the 15th C. work of Francesco di Giorgio Martini. Thus the work of Francesco di Giorgio may have had indirect impact on machine design in the 18th century especially the development of mechanisms for the steam engine.

Most of these new machines however developed out of earlier technologies and in the late 18th and 19th centuries it is unlikely that someone read a book about a machine invention of Leonardo and decided to build it. As Reuleaux noted in his theory of invention, inventors generally observed what was already built, absorbed some new scientific and mathematical ideas, imagined a new application or more demanding performance or economic specifications and then created a new machine. Thus if it is unlikely that Industrial Age engineers were directly influenced by Renaissance engineers, who in the technical world of the 19th century might have been influenced by Leonardo and his contemporaries?

As new machines emerged in the 19th century from inventors and entrepreneurs, another group of engineers were developing a theory of machines based on mathematics and science. It is amongst this group of theorists that there is evidence that Francesco di Giorgio Martini's and Leonardo da Vinci's drawings may have contributed to the science of machines if not to the actual invention of new machines in the Industrial Revolution.

The Age of Enlightenment in the late 18th century, as well as the political revolutions in North America and France, coincided with a renewed interest in Leonardo's art and manuscripts. The defeat of the Lombard Italians by Napoleon's forces led to the removal in 1796 of Leonardo's manuscripts from the Ambrosiana Library in Milan to Paris, an echo of an earlier defeat of Leonardo's patron by Louis XII. An unintended consequence was the study of these manuscripts by scholars in Paris. In 1796 Giovani Battista Venturi, professor at Modena, studied Leonardo's notebooks in Paris and wrote a work entitled, '*Essai sur la ouvrages physico-mathematiques de Leonard de Vinci*'. Venturi is known for his scientific work in hydraulics and the flow of fluids. Trained in Italy in divinity studies he had the background to unravel Leonardo's reverse writing in Italian. His work brought attention to Leonardo's scientific studies that inspired other scientific and mathematical scholars in the second half of the 19th century to examine the manuscripts long neglected in Milan.

Another element in the link between Leonardo and Reuleaux is the writing of French mathematician Chasles in 1837 and Guillaume Libri in 1840. Chasles published a history on methods in geometry in which he mentions an ellipse-drawing mechanism of Leonardo da Vinci, citing of course the essay of Venturi. The Italian Libri wrote a long history of mathematical sciences in Italy in 1840, but he had direct access to Leonardo's manuscripts in Paris. Hart (1961) relates how scholars suspect that Libri stole a section of the Leonardo *Manuscript B* in 1848 and took it to Italy where he sold them in 1867. The manuscript later ended up in the University of Turin. Libri does not have much discussion of Leonardo's machines except to say that he had worked on many sciences as well on mechanics and machines. But Libri's work may have inspired Grothe's study of Leonardo's machines.

The first published facsimiles of Leonardo's notebooks occurred in Paris with the facsimile of the French held Notebooks A–M in 1880 and the facsimile of *Il Codice Atlantico di Leonardo da Vinci* in Milan in 1894–1904, edited by G. Piumati. However there were a number of excerpts of the Notebooks published earlier, such as folios related to the flow of water, released in Bologna in 1828 and a collection of individual folios published in 1872 in

Milan under the title *Saggio delle Opere di Leonardo da Vinci Tavole tratte dal Codice Atlantico*. (See V.P. Zubov, 1968, for a history of the facsimiles of Leonardo's works.) It is perhaps this work that Grothe had access to.

In 1873, Hermann Grothe [b. 1839] of Berlin wrote a series of articles on Leonardo the inventor, in which he cited references to Leonardo's work by the Italian Alessandro Cialdi (1873) who had 24 photographic tables of Leonardo's drawings. Grothe also refers to a Michel Alcan who wrote about a 'scheermachine' of Leonardo in 1870. As a historical note, Grothe, ten years younger than Reuleaux, had attended the Philadelphia Exposition in 1876 as a German trade representative and later wrote an extensive review of American manufacturing technology. Reuleaux was also at Philadelphia as German ambassador to the Exposition. Thus it is likely that these two Berliners were in close contact and that Reuleaux knew of Grothe's research on Leonardo's machines.

There may be evidence that Leonardo's machine drawings may have had some influence on German theoretical engineers such as Franz Reuleaux in the late 19th century, but there is no evidence that his Notebooks, nor the essay of Venturi had any influence on the professor-engineers and students of the Ecole Polytechnique in Paris around in the early 19th century. If Leonardo's work had any impact, it would have been cited in the books of Gaspard Monge, Jean Hachette, or Lanz and Betancourt.

The late historian Eugene Ferguson (1962) wrote that the origins of the Ecole Polytechnique stemmed from the military school in the old city of Mezieres northeast of Paris. Lazare Carnot, Gaspard Monge and Jean Hachette all came from Mezieres to Paris to organize a new curriculum in the theory of machines. Jean Nicolas Pierre Hachette [1769–1834] was a junior member of Monge's department of descriptive geometry upon which the new science of machine kinematics was built. Monge however was called to serve in Napoleon's campaign in Egypt and Hachette was left to design a curriculum in machines that was first offered in 1806. The text for this course was published in 1811 under the title, *Traite elementaire des Machine*. This was an influential book and was even used in the US Military Academy in 1824 or earlier. Hachette's theory of mechanisms was based on the conversion of one type of motion to another and attempted to categorize machines in this manner. Two Spanish students at Ecole Polytechnique published an even more popular book, using Hachette's ideas. Phillipe Louis Lanz and Augustin de Betancourt's work of 1808 was translated into English under the title *An Essay on the Composition of Machines*.

In neither Hachette's work nor Lanz and Betancourt's book is there mention of Leonardo da Vinci or Venturi's essay of 1797. Today this would not be unusual because technical authors normally cite only recent scientific work. But in the 19th century, it was common for authors to review the history of the subject, often over several centuries from the late Renaissance to the early 19th century. For example in Hachette's textbook on machines he references the machine books of Besson (1578), Ramelli (1588) and Leupold (1724). However Leonardo's work is not cited. In 1830, Hachette published a book on the history of the steam engine, *Histoire des Machine a Vapeur* in which he mentioned the ancient Greek and Roman contributions of Hero of Alexandria and Vitruvius as well as the Renaissance engineer Roberto Valturio (1472), but there is no mention of Leonardo's use of steam to drive a vertical shaft turbine wheel that drove a roasting spit, a device often cited by modern authors writing of Leonardo's inventions.

The book by Lanz and Betancourt had a detailed tabular classification of mechanisms and machines based on the change of motion from say rotary to translation or rotary to intermittent motion. In the 158 pages of the English translation, the authors cite well-known machine books of Besson (1578), Ramelli (1588), Strada (1617), Branca (1629), Böckler (1661); but not Leonardo. The most referenced work in Lanz and Betancourt was theatre of machines book of Leupold (1724). The da Vinci scholar Ladislao Reti (1963) had traced the copying of machines in the machine book of Francesco di Giorgio Martini through the 16th, 17th and 18th centuries to Leupold (see Sections II.8 and II.9). Thus we can claim that di Giorgio's machines may have had evolutionary influence on machine theorists in the Ecole Polytechnique and by inference on the British machine theorist Robert Willis as well as Reuleaux's teacher, Ferdinand Redtenbacher in Karlsruhe.

An Italian named Borgnis published a machine classification book in (1818) that added a further six categories or orders to the classification scheme of Lanz and Betancourt with ideas such as *recepteur or regulateur*. Reuleaux also cited this work. But again Borgnis offers no reference to Leonardo. By mid century, the leading theoretician in the theory of mechanisms was the Englishman Robert Willis [1800–1876] who became professor at Cambridge University lecturing on the subject of kinematics of machines. Again there is no reference to Leonardo's machine drawings.

The evidence is clear, that although there were a few published works on Leonardo's machine drawings in the early 19th century, they apparently did not influence the thinking in machine theory in the first half of the 19th century.

Specific discussion of Leonardo's work on machines emerged some 80 years after Venturi's essay in the work of Hermann Grothe of Berlin in 1873 and 1874 who published a series of articles on 'Leonardo Engineer and Philosopher'. Grothe surveyed the earlier work of Venturi on Leonardo. He also cited a paper by Franz Reuleaux on a machine to draw ellipses attributed to Leonardo. Reuleaux created a model entitled 'Leonardo Oval work' in his kinematic model collection based on a double slider mechanism. In describing the ellipse-drawing machine of Leonardo, Reuleaux (1876a) cited the 1837 book of Chasles who had written a history of mathematics. Grothe also mentioned an encyclopedic work of Professor Karmarsch [1803–1879] of the Technical School in Hanover on the history of technology in which some of Leonardo's work on machines was reviewed. Grothe's monograph highlighted a number of basic mechanisms drawn by Leonardo and compared them to the division of machine elements published by Jacob Leupold a century earlier in 1724 (Figure I.19).

Concerning the influence of Leonardo's work on Reuleaux, Grothe provides evidence that Reuleaux was aware of at least some of the machine drawings of Leonardo. In the Preface to his book, Grothe thanked Reuleaux for reviewing the book before publication. He also referred to a collection of Leonardo's drawings and photographs based on the French and Milan codices that were brought to the Royal Industrial Institute in Berlin around 1869–1873. Reuleaux was Professor and Rector of the Royal Industrial Academy in Berlin at the time. Reuleaux's important book on the *Kinematics of Machinery* contains long discussions about the evolution of machines and mechanisms however his only mention of Leonardo da Vinci is in connection with the 'ellipsograph' mechanism. The spirit of Reuleaux's book placed his new theory in a wider context of technical history including references to 16th century machine books. It is not inconceivable that Reuleaux's review of Grothe's manuscript on Leonardo might have reinforced his ideas about evolution of machines and the deconstruction of machines into basic mechanisms.

At the end of the 19th century, several collections of da Vinci drawings and facsimile editions began to appear (see e.g. Zubov, 1968, 2002; pp. 294–296). A facsimile of the Paris Codices was printed in Paris between 1881–1891. The *Codex Atlanticus* was printed in facsimile in Milan between 1894–1904, with excerpts appearing as early as 1872.

In 1899, Theodor Beck of Darmstadt published a German book with a title translated as '*Contributions to the History of Mechanical Engineering*' containing analysis of dozens of mechanisms from Leonardo manuscripts with more than a hundred drawings based on Leonardo's sketches in the volumi-

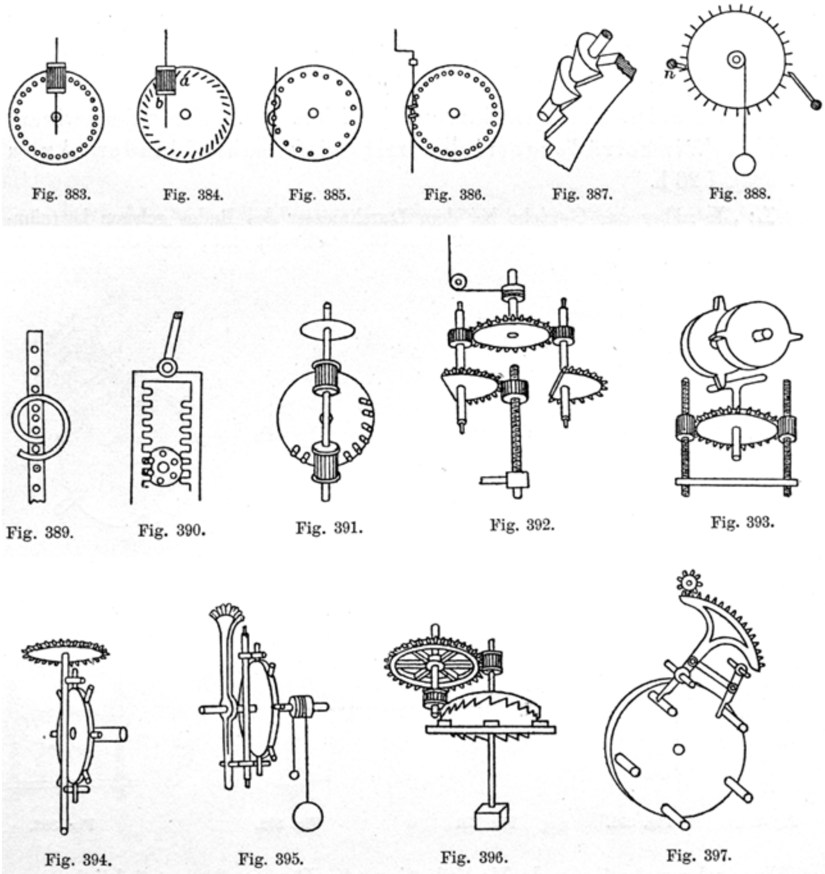

Figure I.19. Compilation of machine elements of Leonardo da Vinci by Theodor Beck (1899) after Grothe (1874)

nous *Codex Atlanticus* as well as the newly translated *Manuscripts A–M* in Paris. Finally in 1922, 17 years after Reuleaux's death, Franz M. Feldhaus published a work describing Leonardo da Vinci as an engineer and inventor. Until Ladislao Reti's comparison of Leonardo's 'elementi macchinali' with Reuleaux's 'constructive elements' of machine design in 1963, the work of the Germans, Grothe, Beck and Feldhaus formed the major interpretation of Leonardo's machine drawings with the modern age of machines.

To return to our question as to Leonardo's influence on 19th century machine design, by the time that scholars such as Venturi and Grothe had published interpretations of Leonardo's work, the pace of technology was in full gear and had surpassed most of the advances recorded and invented by Leonardo in the Renaissance age of machines. Most of those advances

were passed on through the guilds and the encyclopedic 'theatre of machines' books that were published in the 16th, 17th and 18th centuries. (These books are discussed in Section II.9 of this book, as well as in Part IV; see also Table II.4.) The development of new materials in the 19th century such as high strength steel had also changed the way in which basic machine components were designed and manufactured which was dramatically different from the Renaissance age of machines. Still it is likely that *ideas* about the decomposition of machines into basic components, espoused by machine theorists such as Reuleaux, were reinforced by the newly discovered machine drawings of Leonardo in the 19th century.

One area where there may have been direct influence on the design of machines was in the field of flying machines. One of the pioneers of flight Otto Lilienthal was a student of Franz Reuleaux in 1867 at the Royal Industrial Academy in Berlin (Königliche Gewerbe Akademie) six years before Grothe wrote his reports on Leonardo's machines and at a time that Grothe recorded that a collection of notes and sketches of Leonardo were brought to the Institute. Drawings of wing flapping mechanisms by Lilienthal for flying machines have many of the kinematic elements found in Leonardo's manuscript drawings on flying as is illustrated in the discussion in Section II.19 below.

In summary we reiterate a theme of this book once again; although we have no direct evidence for specific inventions of Leonardo being copied in the Industrial Age of machines, the evidence for the evolutionary influence of Renaissance machine engineers through guilds, workshops, and mutual copying from the famous 'theatre of machine' books of the 16th, 17th and 18th centuries is compelling. This thesis will be discussed in greater detail in Part II of this book.

I.7 KINEMATICS OF MACHINES: THE GEOMETRY OF MOTION

Aristotle and early machine theorists such as Archimedes, Hero and Pappas, described the *simple machines* in terms of a balance of forces or what is technically called equilibrium or statics. The *lever*, *screw*, *pulley*, *inclined plane* were analyzed in terms of the force advantage that these components could provide in machines to amplify human and animal muscular power. Although one can still find this approach to machine theory in elementary physics books, the modern view, culminating in the pioneering work of Franz Reuleaux, was the geometric description of machines in terms of a set of mechanisms. This concept is based on the fact that the motion of one link in the mechanism determines the motion of all the other links in the kinematic chain. For example the circular motion of the pedals in a bicycle determines the angular velocity of the sprocket and the chain, which in turn, through the gear train, determines the forward speed of the bicycle and the rider.

The geometric relationship between the motions of all the connected parts in a machine is the subject of kinematics. The French term *cinématique* (from the Greek word for movement) was introduced in 1838 by André-Marie Ampere in his classification of the sciences. (A classic, short history of kinematics is the very readable report of the late historian Eugene S. Ferguson (1962), that can be found on the KMODDL website of Cornell University Reuleaux Kinematic Models; http://kmoddl.library.cornell.edu.) Although kinematics of machines was still in an infant state during the Renaissance, a reading of the *Codex Madrid* of Leonardo da Vinci shows that he was as much concerned with the geometry of motion in machines as with the state of forces in his mechanisms.

In discussing kinematics in the 15th century, one has to remember that many basic concepts pertaining to motion of particles, rigid bodies and fluids had not matured. This includes concepts of velocity, acceleration, angular rotation, composition of motions, the use of coordinates in space and time, as well as the graphical representation of motion. Concepts such as average velocity were discussed by the 13th and 14th century Schoolmen such as those at Merton College. However, the mathematical tools of differential and integral calculus would not be discovered until the time of Newton and Leibniz in the late 17th century. In contrast, during Reuleaux's career in the late 19th century, mathematical kinematics and dynamics reached sophisticated heights especially in the work of Lagrange and Hamilton in dynamics. Thus Reuleaux's contributions to the kinematics of machines were at a more advanced level than those of Leonardo.

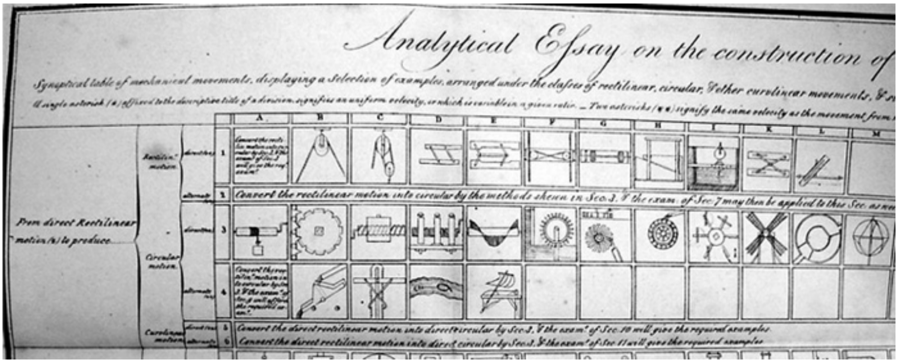

Figure I.20. Table of kinematic motions from Lanz and Betancourt (1809) after Hachette, Ecole Polytechnique

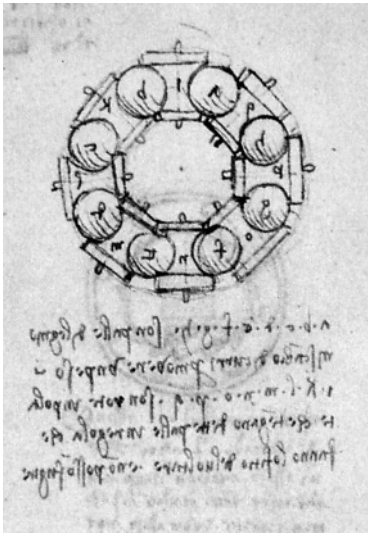

Figure I.21. Sketch of anti-friction ball bearing of Leonardo da Vinci (*Codex Madrid I*, Folio 20v)

The recognition that kinematics was of equal if not paramount importance in machines *vis-à-vis* forces and stresses arose in the work of a group of engineers and mathematicians at the Ecole Polytechnique in Paris led by Gaspard Monge (1795) in the late 18th century. At this time the emergence of the steam engine had triggered a plethora of mechanical inventions and many researchers sought a rationale to try to bring some ordering principle along the line carried out in biology by Linnaeus in 1735 and later in chemistry by Mendeleyev in 1869. Many classification schemes were proposed which were based on the idea of the machine as a device that transformed motion,

Figure I.22. Sketch of planetary gear mechanism of Leonardo da Vinci (*Codex Madrid I*, Folio 13v)

from say circular to rectilinear or from linear to intermittent etc. One of these classification tables is shown in Figure I.20.

Many drawings of kinematic mechanisms can be found in Leonardo's *Codex Madrid*, such as the lever, screw, pinions and toothed wheels, escapements, linkages and belt mechanisms. For example consider the so-called 'ball bearing' of Leonardo shown in Figure I.21, Folio 20v. From the top view it appears as a modern set of steel balls supported by an inner and outer race. However the accompanying text reveals a more complicated device:

> **a b c d e f g h b** are wooden balls, rather than rollers are used to support a weight. **i K l m l n o p q** wheels provided with axels that keep the balls in place so that the balls turn but are unable to escape.

Here Leonardo describes a thrust bearing, not the usual radial ball bearing in modern machines with a similar geometry. He clearly understands the role of different elements in the mechanism in providing constraints so that the mechanism will perform the desired motion.

In another example from the *Codex Madrid*, Folio 13v, he describes the motion of a planetary gear with inner planet pinion **n** and outer planet pinions **a, m** (Figure I.22):

> When the big wheel revolves, pinions **a** and **n** will turn in motion contrary to each other. And pinions **n** and **m** will turn in the same

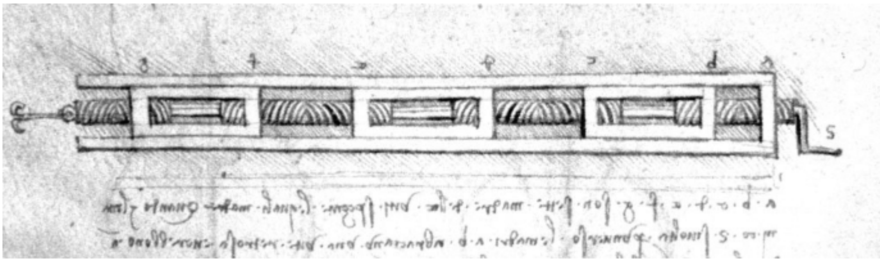

Figure I.23. Sketch of helical screw mechanism, Leonardo da Vinci (*Codex Madrid I*, Folio 57v)

> direction just as the big wheel and pinion **a** will turn in the same direction.

Critical assessments of Leonardo's contributions to theoretical mechanics by Pierre Duhem (1906) and Clifford Truesdell (1968) report that Leonardo did not derive any general principles of mechanics from either his own experiments or mathematical reasoning. They both credit da Vinci with a talent for keen observation and accurate representation of mechanical devices and biological specimens. Throughout the notebooks Leonardo wrote short statements about some philosophical or scientific observation. Both critics however point out that for every aphorism apparently reflecting some fundamental principal discovered centuries after Leonardo, one can often find another espousing a contrary position. The most convincing writing of Leonardo da Vinci however is that accompanying some drawing of a real or imagined machine object. Consider for example the drawing of a shaft with alternating helical screws, Folio 57v. (Figure I.23) Here he is able to generalize from one specific case to another as in the following quotation:

> **–a b c d e f g** are the seven nuts of the disjointed screws. When crank **S** turns in one direction, nuts **a b** which surround an inverted screw, would be inclined to move closer to one another. But since **a** is stationary, the screw, by necessity, must move toward this moveable nut. And the same occurs in the case of nut **b**. Consequently, at an entire turn of the crank, the nut must necessarily proceed by a length equal to two teeth of the screw, and the nut **c** will cover the same distance. Therefore, the screws of nuts **c** and **d** will travel to a length corresponding to 3 teeth, and so forth, with the result that as all the inverted screws have completed one single revolution, the last screw will have moved by a distance equal to 7 teeth because there are 7 nuts altogether.

Concepts of Kinematic Pairs and Kinematic Chains

The idea of a mechanism as a kinematic chain of links, each with geometric constraints with a neighboring link was advanced by the Cambridge professor Robert Willis in his 1841 book on kinematics of machines. Reuleaux's kinematics book of 1875 brought these ideas to maturity with the concepts of *kinematic pairs* and the *kinematic chain* illustrated in Figure I.14. Kinematic pairs also known as 'joints' involve parts that have constrained motion relative to one another. For example, a *revolute joint* involves two parts where one part can rotate about an axis fixed in the other part. A prismatic joint is one where one part can slide or translate relative to one another. Pairs with surface contact Reuleaux called *lower pairs* and joints with point or line contact such as gear teeth in contact, he called *higher pairs*. Different pairs have different relative degrees of freedom. For example, revolute and prismatic pairs have one degree of freedom whereas a ball or spherical joint has three degrees of freedom.

A machine or mechanism made up of rigid bodies can be described as a sequence or chain (circuit) of kinematic pairs as shown in Figures I.14 and I.24. Kinematic chains can be open, closed or branched. Each body is called a link in the chain. Links can have one or more joints between other bodies in the mechanism. Usually one of the links is fixed or grounded. Many mechanisms of the 15th and 19th centuries were closed chains, such as the mechanisms shown in Figures I.3a and b. However a pendulum in a clock is an open link chain. Today most robotic arms involve open link kinematic chains as in Figure I.9. Both Renaissance and Industrial Age engineers used non-rigid links such as springs or elastic beams as well as cables and belts. Reuleaux envisioned the steam or gas in a cylinder as a non-rigid fluid link.

Reuleaux also introduced the idea of non-ideal constraints in machines that he called *force-closed* machines. An example is the rolling contact between a wheel and the road or a wheel and a rail. The contact is enforced by the force of gravity, i.e., the constraint is *force-closed*. However accelerations of the wheel can break this constraint and the rolling constraint will be lost. Revolute, prismatic and screw joints ideally cannot be broken by accelerations. He also believed that the history of the evolution of mechanisms was the replacement of force-closed or incomplete machine pairs by kinematic or geometry-closed constraints, that led to more precise machines.

One of the constructs in mechanism design that evolved from these concepts was the *mobility* or degrees of freedom in mechanisms. For example, given a set of n links or bodies and m joints, how many degrees of freedom will the machine have? In an automobile one requires three degrees of free-

dom, in a robot manipulator arm one wants at least six degrees of freedom. In a hinged door or the control flap on an aircraft we often want only one degree of freedom. Another question is; given a set of links and joints how many different mechanisms can one create from the different combinations of links and joints? These questions opened up a set of topological questions of machine design that developed from the ideas of Franz Reuleaux that we discuss in the following section.

There is no evidence that the work of Leonardo da Vinci had any influence on the concept of the kinematic chain even if the principal kinematic theorists such as Monge, Willis or Reuleaux had had complete access to the Notebooks of Leonardo. Leonardo's work does show a shift in the 15th century to an interest in *motions* in machines as contrasted with *forces*. And he deserves credit for recognizing the existence of basic machine elements in the synthesis of machines. Thus Leonardo's drawings of machine components often show combinations of kinematic pairs, such as gear teeth in contact or elements of chains. This idea evolved into the later drawings of Leupold (1724) that many theorists such as Willis and Reuleaux had used for reference. But it was Reuleaux and his contemporaries in the 19th century that formalized the idea that mechanisms are essentially described by a circuit of geometric constraints (Figure I.24). It is Reuleaux's generalization of this idea to include a whole family of mechanisms under one chain of kinematic constraints that is unique to the late 19th century.

A summary of Reuleaux's general contributions to kinematics are:

(i) the definition of a machine as a chain of constrained elements;
(ii) the idea that machine evolution has progressed from forced-closed mechanisms to more precise chains of kinematic-pairs;
(iii) the recognition that each element in this chain can be understood by looking at the constraints between kinematic pairs;
(iv) the search for a principle of logical synthesis of kinematic mechanisms and his use of a symbolic syntax to classify machine mechanisms;
(v) the use of instant centers or rolling centrodes to represent the relative motion of two kinematic pairs of machine elements.

The last concept is a little obscure but is a beautiful idea. Reuleaux wrote that the general planar motion of any two bodies could be represented as if one body is rolling on another, whether they are constrained or not. Reuleaux may have been the first to provide a systematic discussion of this fact. For each of the moving bodies he derived a path of instant centers or pole-paths (*Polbahnen*, in German, translated at first by Kennedy as *centroid*, who later changed the name to *centrode*). The fact that every constrained motion of a

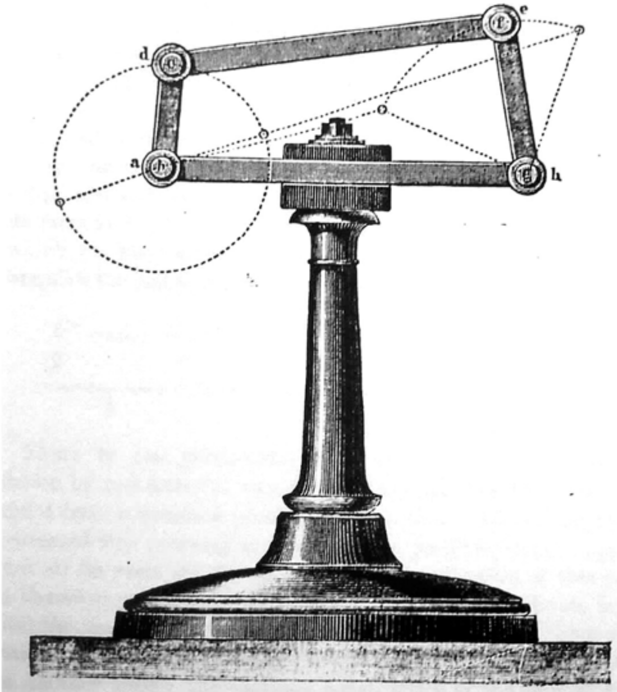

Fig. 180.

Figure I.24. Kinematic chain for a four-bar mechanism (Reuleaux, 1876a)

kinematic pair is equivalent to rolling, and the idea that a machine is a chain of such kinematic pairs, led Reuleaux to redefine the machine, perhaps with tongue in cheek, as a collection of objects in which *everything rolls*.

The geometric nature of kinematics of machinery is made very explicit in Reuleaux's book through the use of particle paths and *Polbahnen*, in which some point on one of the links in the kinematic chain is made to trace out a curve in space as the mechanism is moved through one cycle (Figures I.25 and I.26). For example, the rolling of a small circle or gear on a larger circle will trace out curves called epicycloids. These curves were extremely important in the description of planetary motions in the pre-Copernicus or Ptolemaic geocentric theory of the solar system in the time of Leonardo da Vinci. Aside from their historical importance however, the path points associated with kinematic motions of mechanisms can be quite beautiful as illustrated in the curves in the figure below from Reuleaux's 1876 *Kinematics of Machinery*. These curves are an explicit manifestation of the definition of *kinematics* as the geometry of motion.

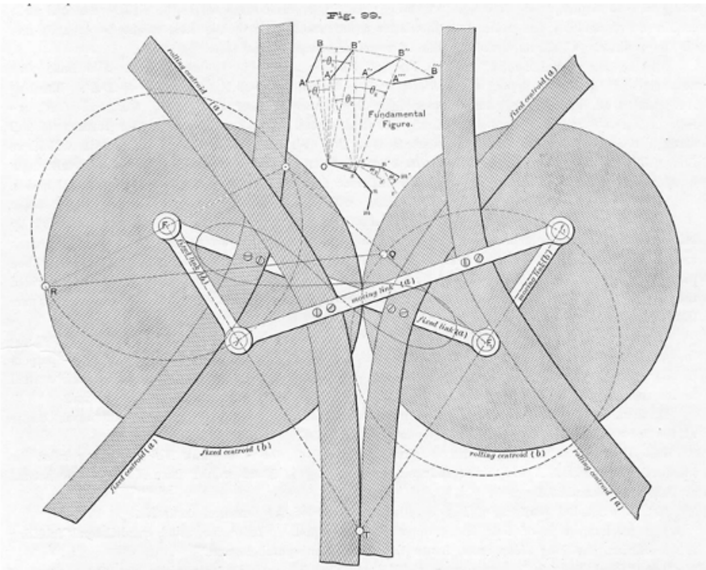

Figure I.25. Centrodes or rolling curves for a four-bar mechanism (Willson, 1898)

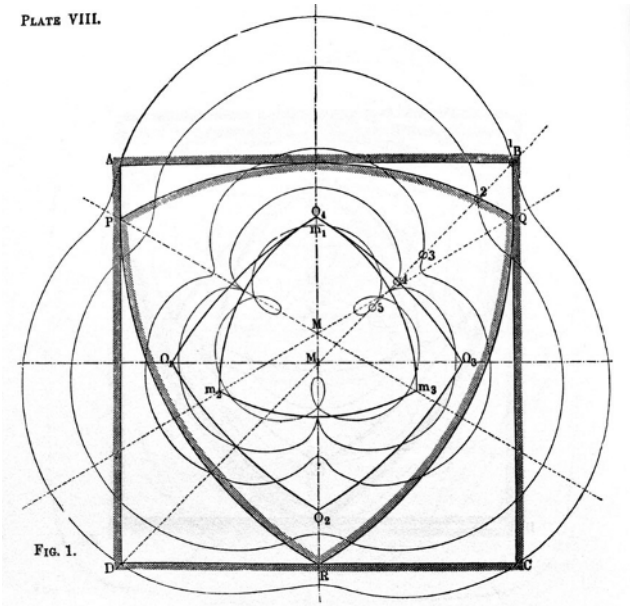

Figure I.26. Path points of motion of a Reuleaux triangle in a square bearing (Reuleaux, 1876a, plate VIII, figure 1)

Dynamics versus Kinematics of Machines

In modern books on mechanics, there is a distinction made between kinematics and dynamics. Kinematics is the description of motion generally with the mathematics of geometry and differential calculus. Dynamics on the other hand treats the behavior of matter under forces governed by the dynamical laws of Newton and Euler. Dynamical laws of physics apply to machines as well as to orbiting planets and satellites. For example, the motion of the pendulum in a clock is governed by the force of gravity and its period is determined by the differential equations representation of Newton's laws of gravity and inertia.

Although Reuleaux's theories about machines were important contributions at the time, his theories were based largely on geometric ideas (or what Reuleaux called *Phoronomy*) and not on dynamic principles that were later incorporated into the theory of machines. Nor did Reuleaux treat the problem of rolling bodies and so-called *non-holonomic constraints*. Modern texts on multibody dynamics and robotics treat both kinematics and dynamics in a systematic way. These dynamic theories however, view the machine as a deterministic entity whose behavior could be uniquely predicted and controlled by use of the Newton's laws of motion. The distinction between kinematics (governed by geometry) and dynamics (governed by laws of physics) was not known in the Renaissance of Leonardo and his contemporaries. Leonardo da Vinci knew however that geometry was important to the study of machines.

Recently there have been new discoveries in dynamics under the mantle of '*chaos theory*', (see e.g. Moon, 1992). Modern engineering scientists have discovered that many machine mechanisms can exhibit small amounts of unpredictable or chaotic dynamics due to the inevitable imperfect nature of the machine as constructed, including friction, backlash and elastic flexibility. Examples include chaos in gears and chaos in ball bearings. This has suggested that a modern theory of machines should admit a certain measure of chaos or even randomness in the behavior and that in some cases this small unpredictability may be beneficial to the successful operation of the machine. The nature of unpredictability in machines was not ignored is the 19th century, especially amongst clock analysts (see e.g. Moon and Stiefel, 2006).

Reuleaux seems to have recognized the fact that unilateral constraints or what he called 'force-closed' constraints, were a source of "*clattering and jerking in their force-closed working*". He said, the scientific designer tries to eliminate unilateral constraints "*until all indefiniteness is removed*". He also acknowledged the problem of determining friction forces in mechanisms, which today are recognized as a major source of chaos in mechanical systems.

The problem of friction in machines was also of concern to Leonardo da Vinci who proposed various bearing concepts to minimize friction loss in machines.

In antiquity and the Middle Ages, machines generally resided in craftsmen's minds only to be realized through the skills of the workshop. In the Renaissance we see the emergence of graphical static representations of machines that have pictures of physical machine elements that can begin to be used to construct working devices, especially in the work of Leonardo da Vinci. In the late 18th century Monge and his Parisian colleagues at Ecole Polytechnique represented the machine with descriptive geometry. By the late 19th century, Reuleaux and his contemporaries reduced the machine to a set of abstract symbolic elements in a circuit. In the 20th century the motions in machines were represented by beautiful mathematical curves, differential equations and topological ideas in the machine designers brain. Today the complex machine exists again as an abstract construct, but now in a multibody code in a computer and not in a human brain.

I.8 VISUAL AND TOPOLOGICAL THINKING: REULEAUX'S LANGUAGE OF INVENTION

Written language is a set of icons adopted by a community to codify and transmit information. In contrast to our digital age of binary symbols, information in past millennia was codified in complex pictograms, symbols and alphabets. In the evolution of machines, codification of machine geometry and topology was often represented by graphic pictograms that gained status of a universal '*lingua franca*' of machine design. Examples of common representation of machine elements and kinematic mechanisms can be found in artifacts of ancient Babylonian and Egyptian cultures. This process began with symbols for the 'simple machines' such as the lever, wheel, screw, pulley and inclined plane. By the late Middle Ages and Renaissance, this graphical machine language was highly developed. Complex machines can be found in the 13th century sketchbook of Villard de Honnecourt (also *Wilars de Honecort*) and in the 13th century machine drawings of al-Jazari. By the early Renaissance of 15th century Italy, this art reached maturity in the work of the artist-architect-engineers.

In machine books of the 15th and 16th century one can see the same classes of mechanisms in books by a dozen authors from different parts of Europe. Pumps, endless screws, toothed wheel pairs, chain of pots, clock escapements and many other mechanisms are represented in this universal machine language. In the sketchbooks of Leonardo da Vinci, such as the *Codex Atlanticus* or the *Codex Madrid*, there are hundreds of drawings of gear mechanisms. The shape of the gears and their teeth vary considerably and the applications are many and varied, however there is no mistaking this kinematic pair. Similar machine books appeared in China as in the summary of Chinese technology, *T'en-Kung K'ai-Wu* (1637) or *The Book of Ingenious Machines, Qi Qi Tu Shou* (1627) of the Jesuit Johann Terentius (a.k.a. J. Scheck) and Chinese engineer Wang Cheng that was a translation of several parts of Western machine books. (The Sinologist Joseph Needham (1965) has written an extensive history of Chinese contributions to mechanical engineering.)

The use of pictorial and graphical language as a primary tool for communication of technical information has been advanced by the historian Eugene Ferguson (1977, 1992). In a recent book Arnold Pacey (1999) discussed the importance of both pictorial and diagrammatic visual thinking in science and engineering. The origins of development of a visual language for engineering and science can be found in the early Renaissance. Perspective and drawing to scale became important in communicating both architectural and engineering designs according to Pacey (1999). The historian Alfred Crosby

has made the point that visualization was very important in the development of a new way of scientific thinking. The importance of literal education was challenged by ideas based on visual and abstract non-verbal constructs. (See also Section II.1 for a discussion of kinematic perception and the brain.) The evolution in visual language of machine knowledge took a similar path from literal symbols of gears and wheels beginning in the ancient cultures to more abstract network and circuit symbols of Reuleaux and other 19th century mathematical engineers.

In Western culture, historians often try to assign invention to specific people and the patent system is a codification of this tradition. This has led to claims of copying or plagiarism when similar machine components appear in machine books over the centuries and across many cultural and language groups. But another interpretation is that these so-called ‘inventions’ arose out of the common language of machines developed over countless generations and are the result of the evolution of a graphical representation of humankind’s understanding of geometric, topological, and kinematic constraints between mechanical objects which we call machines.

A similar set of graphical tools is associated with static structures in architecture. The use of geometric constructs such as rectangles, triangles, arcs of circles to represent the built environment of buildings, dams, fortifications, churches mosques, towers etc. also developed over many centuries. It is no accident that major machine designers of the Renaissance such as Brunelleschi, or Francesco di Giorgio Martini were both architects and machine engineers. We can see in the sketchbooks of Leonardo da Vinci hundreds of geometric shapes side by side with renderings of designs for buildings, dams and machines. This connection between machines and architecture can also be found in the 19th century work of the machine theorist Robert Willis of Cambridge who published books on both kinematics of machines as well as the history of construction of British cathedrals. (See also Feldhaus, 1953, and Ceccarelli and Cigola, 2001, for a review of mechanism drawings from the Middle Ages.)

Unlike most architectural objects, machines have a dynamic or kinematic relationship between the solid and fluid material objects that comprise the machine. The graphics must embody geometric constraints such as gear teeth in contact or the rolling of a wheel over a ground plane. The graphical icon or symbol must represent not only the geometric relationship at a particular time, but also the constraints over an entire cycle of positions as in the movement of a pump piston in a cylinder. The use of the term *topological thinking* is meant to capture this idea, which must have developed over many

millennia; the concept of invariant geometric relationships that are preserved in machine motions when the dimensions, materials and application of the machine or mechanism change. Recently it has been suggested that the kinematic geometry of mechanisms might have the same *a priori* status as the axioms of Euclidian geometry.

Although textual descriptions of machines can be found in the work of Roman engineers such as Pollio Vitruvius (c. 27 BC), extended catalogs of machines and kinematic devices began in the 15th century, such as those of Konrad Kyeser, Marianus Jacobus, also known as Taccola and Francesco di Georgio Martini as well as the posthumous Codices of Leonardo da Vinci (e.g. *Codex Madrid I*, 1493). These were followed by others such as Besson (1578), Ramelli (1588), in the 16th century and later by Leupold (1724) in the 18th century. The similarities in the machines depicted in these books are striking. However, these 'theatre of machines' books lacked a mathematical underpinning that began to emerge in the late 18th century (see Section II.9).

The formal codification of geometric machine constraints began in the work of the French thinkers at the Ecole Polytechnique in Paris under Gaspard Monge [1746–1818] in the late 18th century. Monge (1795) proposed that all engineering students be taught *descriptive geometry*. Descriptive geometry, sometimes called 'projective geometry' is the accurate representation of three-dimensional objects on a two-dimensional plane. Monge developed rules for rigorously projecting the geometric features of a solid onto two or more perpendicular planes. This became the foundation of what two centuries of students called 'mechanical drawing'. The foundations of projective geometry can be seen in earlier theorems of Pascal and Desargues. Monge's descriptive geometry was used at the US Military Academy in the early 19th century by Charles Davies (1859), who published his lecture notes. In his Preface, Davies stated that

> In France, Descriptive Geometry is an important element in scientific education: it is taught in most of the public schools and is considered indispensable to the Architect and Engineer.

Davies noted however that descriptive geometry was not widely used in the United States at mid century.

Monge's contemporary at Ecole Polytechnique, Jean N.P. Hachette in 1811 constructed a table of basic kinematic elements based on the transformation of motion; e.g. from circular to rectilinear or circular to alternating motions. This classification scheme for machine kinematic elements was very popular up until the work of Franz Reuleaux in 1875. A variation of Hachette's table can be found in Figure I.20 from the work of the Italian

Borgnis (1818) describing the composition of machines. On the left hand column one can look up the type of input-output behavior one wants the mechanism to have; e.g. continuous rotary to intermittent motion, etc. The row to the right then shows a set of icons representing different possible mechanisms that will exhibit this characteristic motion. Such tables were very popular in the 19th century. This classification scheme for machine mechanisms using a tabular format predated the periodic chemical table of the Russian Dimitri Mendelayev in 1868.

Reuleaux's theory of kinematic motions in machines departed dramatically from these earlier schemes of mechanism classification based on the input-output motions. Instead he based his classification on geometry and topology of the connected kinematic elements in the mechanism. And while pictorial representation is beautifully represented in Reuleaux's books, his use of textual symbols was the beginning of a step away from a graphical language in machines to more abstract mathematical symbols and constructs such as differential equations and matrices.

Up until the late 18th century, the Aristotelian theory of so-called simple machines, the lever, screw, wheel, wedge, etc., held a dominant role in machine theory. Reuleaux is credited with the idea of a mechanism as a chain or network of geometrically constrained bodies. But the germ of this idea appears earlier in Willis in the preface to the second edition of his book:

> For every machine will be found to consist of a train of pieces connected together in various ways, so that if one can be made to move they all receive a motion, the relation of which to that of the first is governed by the nature of the connection.

Willis's plan was "*to reduce the various combinations of pure mechanism to system, and to investigate them according to geometric principles alone*".

Before the late 18th century, machines were often classified according to application; pumps, machine tools, military machines etc. Monge and his contemporaries instead grouped machines according to how they changed motion, from say circular to rectilinear or from rectilinear to alternating motion. Willis criticized this classification, as did Reuleaux some years later. He pointed out that the conversion of circular to rectilinear motion as a method of classification *lacked uniqueness*, thus it could not capture the essence of the mechanism. For example in the four-bar linkage shown in Figure I.24, the continuous motion of the crank on the left creates a rocking motion of the right-hand link, sometimes called a *crank-rocker* mechanism. But if one grounds the crank link, circular motion of the new crank determines circular motion of the new follower link. This new mechanism, using the same

kinematic chain, is called a *drag-link* mechanism. Thus several input-output motions can be obtained from one kinematic chain of links and joints, depending on the relative lengths of the links and which link is grounded. This was the basis of Willis and Reuleaux's arguments on the non-uniqueness of the French tabular classification of mechanisms based on input-output motion characteristics.

Franz Reuleaux's major work in kinematics was first published as a series of articles by the Prussian Society for the Advancement of Industry in 1871–1874 and published as a book in 1875 under the title, *Theoretische Kinematik: Grundzüge eine Theorie des Maschinenwesen*. It was translated almost immediately into French, Italian and English, the latter by Professor Alexander B.W. Kennedy of University College London in 1876 under the title, *The Kinematics of Machinery: Outlines of a Theory of Machines*. The ideas that Reuleaux presented in this book influenced the field of machine design for a century. Reuleaux published a sequel to this work in 1900, called, *Lehrbuch der Kinematik; Zweiter Band. Die Praktischen Beziehungen Kinematik zu Geometrie und Mechanik* (roughly, Textbook in Kinematics, 2nd Volume. The Practical Relationship between Kinematics and Geometry and Mechanics). However, by the new millennium the science and design of machines had moved away from kinematics into new areas of thermodynamics, materials and electrical machines and Reuleaux's last work did not have the impact of his earlier work. In 1893, Reuleaux published the fourth edition of his widely used *The Constructor*, in English for the first time. (The use of the French term 'Constructor' which can be translated as 'designer' was unfortunate, as in the US it is associated with civil engineering not mechanical engineering.) However, in this edition, which was translated by Henry Suplee, an early figure in the American Society of Mechanical Engineering, Reuleaux presented a summary of his kinematic theory of machines along with his detailed descriptions, technical data and formulas for the design of machine elements.

As described earlier, Reuleaux's key idea in his kinematics is that all mechanisms with rigid bodies can be studied by looking at the relative motion of pairs of elements or joints. Reuleaux went beyond Willis in stating that, all determinate mechanisms are formed by a kinematic chain of joint pairs, recognizing the important fact that the grounded elements are often part of the chain of kinematic links (Figure I.24). He implicitly introduced, perhaps for the first time in engineering, topological ideas into kinematics. By changing the ratio of link lengths and diameters of cylindrical joints, he was able to generate a large class of mechanisms all of which have the same

sequence in the chain of geometric constraints between pairs. For example, he was able to show that a dozen or more of rotary motors and pumps were all members of the same kinematic family, even though many had different inventors. Reuleaux believed that this methodology would provide a tool for kinematic synthesis or what is called today, *topological synthesis*.

Reuleaux's Topological Theory of Kinematic Mechanisms

Topology is defined as that branch of mathematics that deals with the most general properties of mathematical objects such as geometric figures. In the 19th century, topology was known by the Latin *geometrica situs or analysis situs*. The term *topology* originated from a book title of the German mathematician Johann B. Listing (1848) of Göttingen. However the subject did not mature until the 20th century beginning with the work of H. Poincaré. One of the earliest theorems in topology is due to L. Euler (1736). This theorem is described in terms of polygonal nets or circuit networks made up of e nodes, k links and f faces. Euler's rule states that; $e - k + f = 1$; i.e., the number of nodes, geometric faces or polygons enclosed by k lines or links is related for any planar net where every link is connected to two nodes.

Kirchhoff also used similar general relations in positing his theory of electric circuits in 1847. In the case of a network of mechanical linkages connected to form a movable mechanism, similar topological relationships can be found. With so many of the pioneers in topology from late 19th century Germany and Europe, it is not surprising that topological thinking appeared in the work of Franz Reuleaux's theory of kinematic machines especially the idea of a kinematic chain or network.

The most familiar paradigms in the topology of geometric objects are the Möbius band, knot theory, tiling of surfaces, networks, the Klein bottle and the famous topological equivalence of the coffee cup and the donut or torus; i.e. each has one essential hole. This latter idea in the topology of geometric objects is the notion that two objects are topologically equivalent if one can transform one into the other, without tearing or ripping. Thus the term '*rubber sheet topology*'.

In order for two objects to belong to the same topological class they must share some common general relationship, as in Euler's network problem. The objects must be shown to be equivalent under a proper set of transformations or group. It is this idea of topology that Reuleaux used in his theory of mechanisms. Starting with the concept of a kinematic chain as a sequence of kinematic constraints or joints between neighboring links, he expanded or contracted some of the dimensions of the links and joints to generate a class

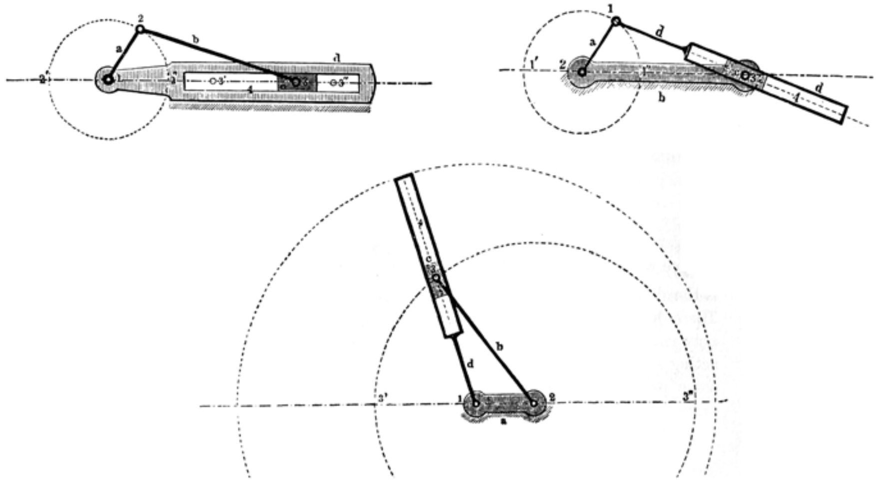

Figure I.27a. Inversions of the slider-crank mechanism (Reuleaux, 1876a)

of mechanisms that have a common sequence of joints and links. Aside from an interesting mathematical exercise, Reuleaux claimed that this searching the space of mechanisms within his defined kinematic group was an essential tool for kinematic synthesis and invention. Reuleaux enumerated six ways to generate a class of mechanisms with the same kinematic joint sequence in the chain;

> ***Inversions***: changing the grounded element in the chain of kinematic pairs.

Reuleaux recognized that in a kinematic circuit with four degrees of freedom of motion, any one of the links could be grounded, eliminating three degrees of freedom, to form a single degree of freedom mechanism. Thus a four-link slider crank chain could become four mechanisms (Figure I.27a).

> ***Expansion of elements***: enlarging or changing the scale of different links in the chain.

This idea is closest to the modern concept of topological transformations or ‘rubber sheet’ topology. Reuleaux was able to show that the slider-crank mechanism, used today in millions of vehicle engines, was kinematically equivalent to the eccentric mechanism shown in Figure I.27b, in which he stretched the cylindrical bearing to where it was larger than the length of the crank.

> ***From plane to conic chains***: redefining a planar linkage to one on a sphere.

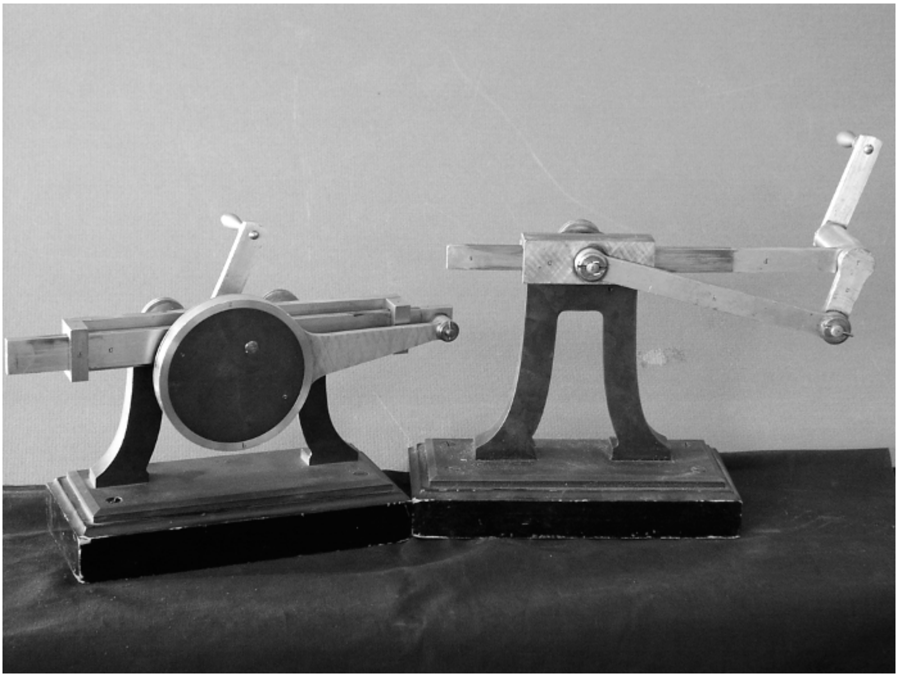

Figure I.27b. Expansion of elements of the slider-crank mechanism (right) into an eccentric mechanism (left). (Models from the Cornell Kinematic Mechanisms Collection: See models C-2, E-2, on the KMODDL website)

In this extension of a class of mechanisms, Reuleaux took a linkage in a plane surface and mapped it onto a spherical surface. For example he showed that the universal or Hooke's joint was identical to the motion of a four-link chain on a sphere. He also used topological thinking to relate the universal joint to a spherical engine, also mapping the parts onto a set of links on a sphere.

Reduction of kinematic chain elements: reducing the length scale of one link to zero while maintaining the geometric constraint.

An example of this method is in the case of the slider crank in which the length of the slider is reduced to zero and the cylindrical joint moves in the slide. Here Reuleaux essentially substitutes a lower kinematic pair, i.e. two flat sliding surfaces, with a higher kinematic pair in which the sliding cylinder has only line contact with the linear guide.

Augmentation of kinematic chains: serial linking of kinematic chains.

In this method, several basic kinematic chains are coupled together. (This would not be a topological operation.)

Generation of compound chains: the use of more than one circuit of kinematic chains. (This would not be a topological operation.)

In this method, adding extra links and joints as in a six-bar chain of links can extend a one degree of freedom kinematic chain using four links. An example is shown in Figure I.30.

Reuleaux's Symbol Notation

Reuleaux's attempt to place machines in the context of geometry and topological invariants led him to propose a symbolic language to codify these invariants. The key to his classification was the recognition that every mechanism could be represented as a chain of kinematic pairs or constraints. Each constraint involved a geometric relation between adjacent parts. A piston in a steam engine, for example, is confined to slide back and forth in the cylinder. Each link on a bicycle chain is constrained to rotate about an axis relative to the adjacent link and so on. Each constraint he represented as a symbol, letters with superscripts and subscripts.

In chemistry and biology attempts were made to classify the objects of these sciences with tables and abstract notation. The periodic table of elements in chemistry by the Mendeleyev and Myer appeared in the middle of the 19th century. Similar attempts at classification of machines were also attempted. For example Jean N.P. Hachette, in 1811, constructed a table of mechanisms according to how these mechanisms change motion from say circular to linear motion or from circular to intermittent motion. Charles Babbage (1826) of computer fame, created a mechanical notation using lines and arrows to show how one part of a machine drives another. Unlike Hachette, Babbage's notation tried to show relationships between different parts of the machine. However, the notation required a two-dimensional tabular array for each device not unlike that in a music score. He presented an example of an hour counting mechanism for a clock that encompassed two full pages. There was a similar effort by Cambridge professor Robert Willis (1841) who devoted the entire Chapter X of his book to '*mechanical notation*'. His method is similar to Babbage's in that the machine is represented by a table with entries for names of the parts, the numbers of gear teeth, angular velocities, and the type of motion, i.e., steady, oscillatory, or intermittent.

In his quest for an alphabet of machine devices, Reuleaux built the world's largest collection of machine components, a dictionary of sorts of over 800 models. Using his symbolic system, along with his models, Reuleaux sought to deconstruct every machine that had been or would be invented in the future, a Genome project for the Machine Age.

A century earlier, in 1735, the Swedish biologist Carolus Linnaeus had constructed a taxonomy for plants and animals using ideas of species, genus, family, orders, etc. Some of these biological taxonomies were based on physical similarities and some on evolutionary ancestors. Initially, Reuleaux tried to classify machines based on function, such as *guiding*, *storing*, *driving*, and *forming* or *place-changing* machines versus *form-changing* machines. He was perhaps influenced by Borgnis (1818) in his *Traite complet de méchanique* who divided machines into six categories; *réceptors*, *communicateurs*, *modificateurs*, *supports*, *régulateurs*, and *opérateurs*. Reuleaux however abandoned the function-based approach, in favor of a syntax-based methodology using a model based on linguistics rather than biology, a model patterned after chemistry. Each machine is comprised of a chain or network of constrained links and the key to distinguishing one machine from another was the sequence of these different link joint pairs. Each kinematic pair could be written as a symbol and the entire machine as a sequence of symbols. A factory is then a sequence of symbolic words or a sentence representing a complex assembly of machines.

Reuleaux introduced his symbol notation in Chapter VII of *Kinematics of Machinery* (1876). His notation essentially maps kinematic constraint pairs onto a set of symbols. For example, Reuleaux used the symbol ‘C’ to represent a cylindrically coupled or revolute kinematic pair. He used the symbol ‘P’ to represent a prismatic kinematic pair, ‘S’ to represent a screw pair.

Reuleaux’s symbol notation has three different kinds of symbols:

Class or name symbols; [S screw, P prism, C cylinder, K cone, V vessel, etc.]

Form symbols; [+ full body, – open body, z teeth (Zahn), λ liquid, γ gas]

Symbols of relation; [. . . linkage, ____ grounded link, $\|$ parallel axes, $|$ co-axial, $+$ crossed at right angles, $<$ non-right angle]

Examples of a kinematic circuit with symbols are shown in Figure I.29. The ‘compressed’ circuit notation is illustrated in the table in Figure I.28. Examples of his compressed notation include:

$(C_4^{\|})^d$;	Four-bar linkage (link ‘d’ grounded)
$(C_3^{\|} P^T)^d$;	Slider-crank (link ‘d’ grounded)
$(C_3^T C^<)^{a/b}$;	Universal joint
$S' P' C'$	Screw actuated prismatic slide

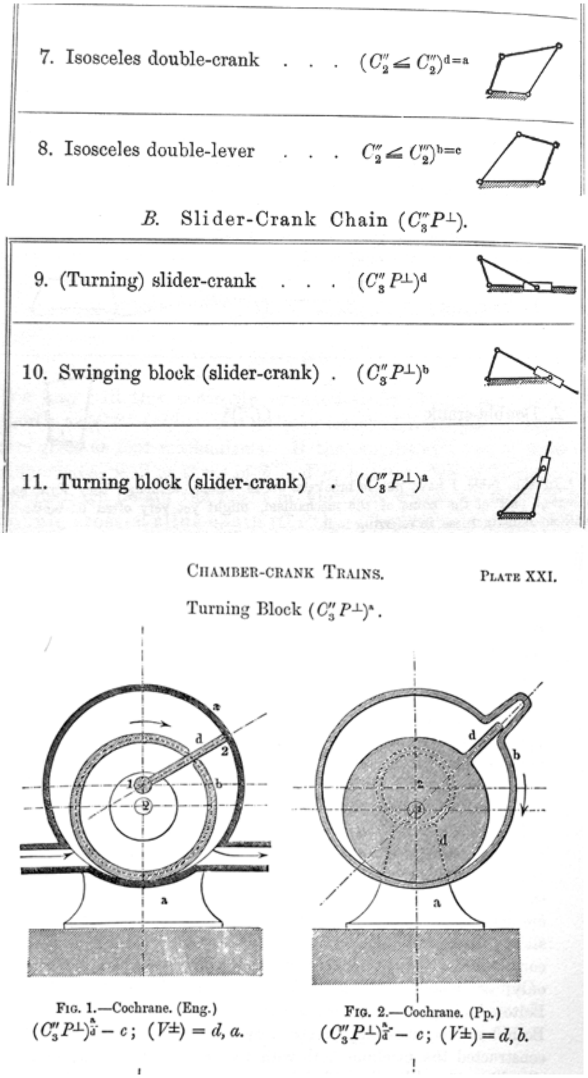

Figure I.28. Sample symbol table for mechanisms from Reuleaux's *Kinematics of Machinery* (1876), for slider linkages and rotary pump-engine mechanisms

For a steam engine Reuleaux used the symbol:

$(C_3^{\|} P^{T})^{d/c};\ (V^{\pm}) = c, d;$ Steam or gas engine

The first symbol for a four-bar mechanism indicates four cylindrical or revolute (rotary) joints, all axes parallel as notated with the superscript on the letter C. The four links are labeled a, b, c, d. The superscript 'd' indicates that the d-link in grounded (see Figures I.28 and I.29).

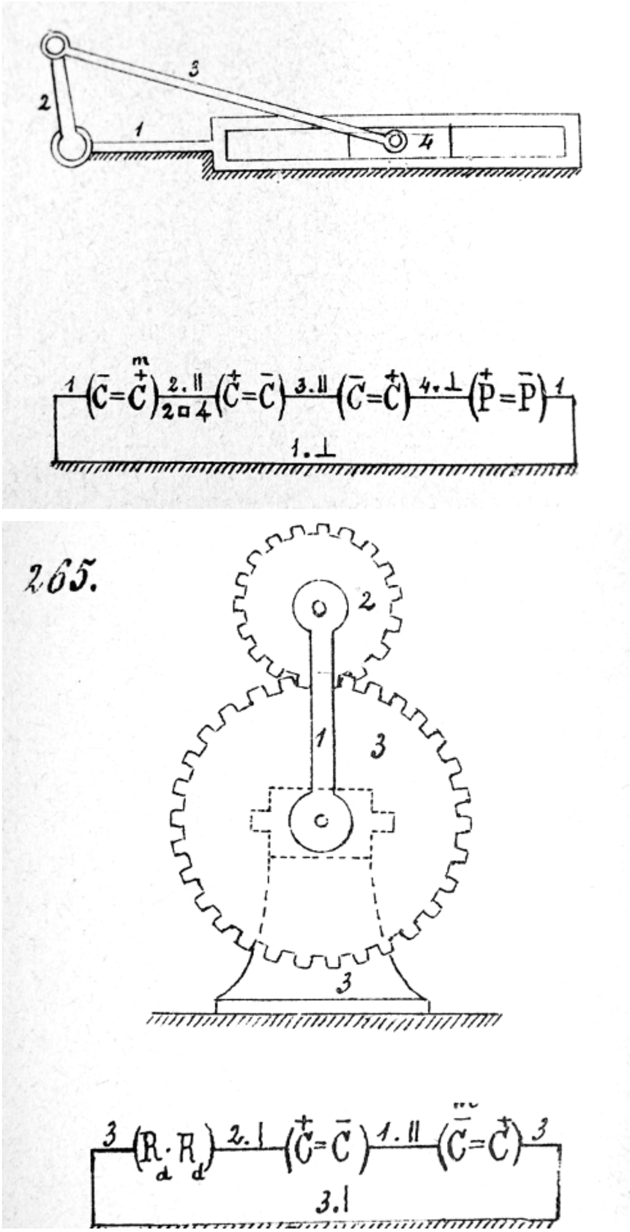

Figure I.29. Kinematic circuits and symbols based on Reuleaux, published by Francesco Masi (1883)

The second symbol above for the slider-crank mechanism is the compressed notation for three revolute joints with parallel axes and a prismatic joint, i.e. linear sliding, where the direction of sliding motion is transverse to the rotary axes. (Reuleaux used an inverted Tee without serifs to indicate a perpendicular axis.) His notation does not include any information of mass or moment of inertia. In this sense it is pure geometry and topology based. For example, a flywheel cannot be represented as a carrier of kinetic energy, since his notation is not based on dynamics, forces, or energy.

The Italian machine theorist Francesco Masi (1883, 1897) published an extensive set of kinematic symbols for dozens of mechanisms in his 1883 book. Two of these are shown in Figure I.29.

Another example of a generating class of mechanisms is the universal joint (Cardano and Hooke) that can be shown to have the same symbol as a spherical mechanism for a rotary steam engine patented in 1836 by Taylor and Davies. The kinematic chain symbol for both is $(C_3^T C^<)^{a/b}$. Here the second superscript $<$ represents an axis at an angle to the other revolute axes. The superscript 'a' indicates the name of the fixed link and the symbol 'b' the name of the driven link.

Reuleaux's use of inversions and expansion of elements implicitly uses another set of data for the mechanism, namely the relative sizes of the links and constraint elements such as diameters of cylindrical bearings and size of the slider. For example, in the case of the slider crank, he labels each link $\{a, b, c, d\}$ where the slider is 'c'; and he labels each of the three cylindrical joints with $\{1, 2, 3\}$ where link 'a', is between joints '1' and '2'. These symbols were engraved on the links of many of his kinematic models. (See the KMODDL website of Cornell Reuleaux models to view the engravings on the links and joints.)

An important concept in Reuleaux's theory is his use of *inequality relations for machine synthesis* or the idea of relative sizes of the bearing and link geometries. Although this is not explicit in his text, it is clear from his writing that changing dimensionless, geometric groups can generate a family of mechanisms with the same constraint symbol. For example we could think of the symbol for the slider crank as incorporating dimensional variables (as in the modern sense of object oriented programming); i.e., $C_3^{\|} P^T\{L_a, L_b, L_c, L_d, d_1, d_2, d_3, w\}$, where the 'L's are the lengths of the links (L_c is the length of the slider) and the 'd's are the diameters of the cylindrical joints. The width of the slider is 'w'. Reuleaux is then able to generate a family of slider crank mechanisms by changing the relative lengths as

represented by inequalities. For example, the classic slider crank involves the inequalities;

$$d_1 < L_1, \quad d_1 < L_4, \quad \text{etc.}$$

i.e., the diameters of the cylindrical joints are less than the lengths of their neighboring links. However, Reuleaux then asked the reader to imagine the mechanism with $d_1 > L_1$ or $d_2 > L_1 + L_2$, and proceeded to illustrate these 'new' mechanisms, which all have the same symbol word, but have different inequality relations between the link and cylinder pair dimensions. Some of these mechanisms he reminded the reader had been invented earlier. In making these expansions, Reuleaux attempted to 'exhaust' the topological possibilities of the basic slider crank kinematic chain to show '*the possibility of the machine*'. Two members of this family are shown in Figure I.27b in which Reuleaux showed how the crank was related to the eccentric mechanism. Using his topology based methodology he was able to derive 54 mechanisms from the four-bar linkage and classify them into 12 classes.

Although Reuleaux's ideas about kinematic pairs and open and closed chains in mechanisms have survived in texts today, his symbol notation all but died with his passing (see Hartenberg and Denavit, 1964). However, in the modern field of computational multi-body dynamics, graph theory symbol notation is used to represent the connection properties between bodies in a complex machine.

GRÜBLER'S THEOREM; MOBILITY OF MECHANISMS

In analogy to electrical circuits, the closed mechanical circuit can be generalized into multiple circuits or kinematic network, called compound linkages, shown in Figure I.30.

James Watt used compound mechanisms in the design of his steam engines, as well as by George Stephenson in his steam locomotive engines. One of the properties of compound linkages is the existence of topological invariants. Topological relationships describe general properties of geometric objects independent of their specific dimensions and shapes. For example, if 'n' denotes the number of links in a planar kinematic network, 'r' the number of revolute or cylindrical joints, and 'F' the number of degrees of freedom in the mechanism, sometimes called the *mobility*, then the following relationship can be established:

$$2r - 3n + (3 + F) = 0 \tag{1}$$

or

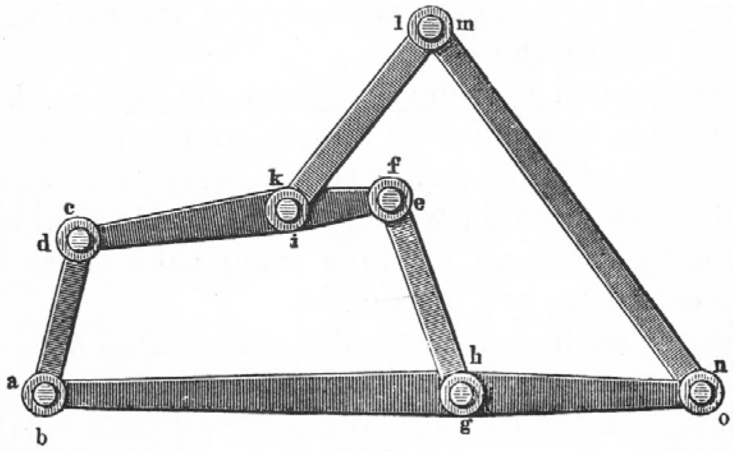

Figure I.30. Six-bar compound mechanism with one degree of freedom (Reuleaux, 1876a)

$$F = 3(n - 1) - 2r. \tag{2}$$

For one degree of freedom or, $F = 1$,

$$r = \tfrac{3}{2}n - 2. \tag{3}$$

The conventional derivation of equation (2) begins with a set of n links in the plane with $3n$ degrees of freedom (two translations and one rotation) with one grounded link leaving $3(n-1)$ degrees of freedom. A set of r lower pair joints such as turning pairs or revolute joints removes $2r$ degrees of freedom hence the expression above. The interpretation of F is that $F = 1$ indicates a perfect mechanism where the movement of one link determines the movement of all the rest of the links. If $F = 0$, the arrangement of links forms a statically determinate rigid truss or structure and if $F = -1$, the structure is statically indeterminate and the internal forces are dependent on the elastic properties of the links.

Relations (2), (3) for $F = 1$ were posited by Martin Grübler in an 1883 paper in *Der Civilingenieur* and later in his 1917 book on kinematics, *Getriebelehre* (Berlin). Grübler [1851–1935] was a professor at the Technische Hochschule Dresden and was influenced by the work of Franz Reuleaux. These relations hold for planar mechanisms. Similar equations can be written for spatial linkages. Grübler credited two mathematicians for this criterion, Sylvester and the Russian Chebyshev.

A modern discussion of the use and limitations of mobility criteria may be found in the English texts of Burton Paul (1979), D.C. Tao (1967), Joseph

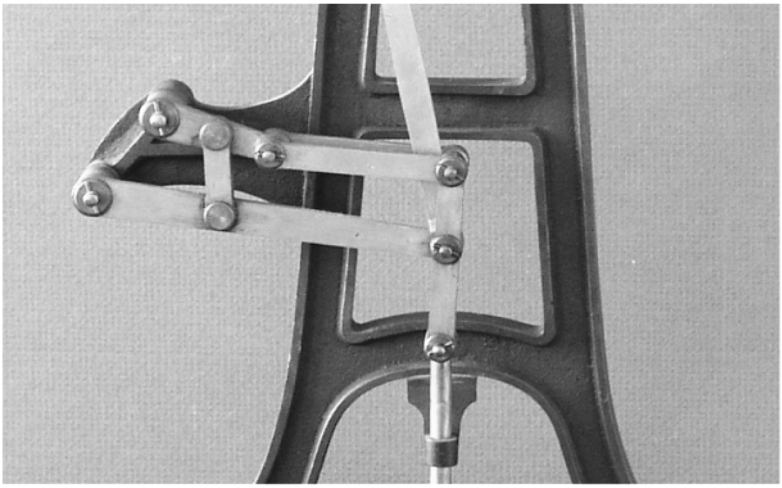

Figure I.31. Reuleaux straight-line mechanism with six links and seven joints. ($F = +1$) Model S-32 in the Voigt catalog. (Cornell Kinematics Model Collection)

Shigley (1963), Richard Hartenberg and Jacques Denavit (1964) and Arthur Erdman and George Sandor (1997).

In relation (2), r, n, F are integers and the number of degrees of freedom assumes that one link of the network is grounded. The minimum number of links for $F = 1$, is $n = 4$, which gives $r = 4$. The integer requirement implies that the number of links n must be even, which leads to the sequence of possible single degree of freedom compound mechanisms:

$$\{(n, r) = (4, 4), (6, 7), (8, 10), (10, 13) \ldots\}.$$

An example of a six-bar linkage with seven pin joints and one degree of freedom is the approximate straight-line mechanism of Reuleaux Model S-32, from the Voigt catalog of Reuleaux's models (Figure I.31).

In Figure I.31 we can see seven joints, ignoring the upper crank arm and the lower slider arm that are not essential to the mechanism. In this mechanism there are two links with three joints, one of the upper horizontal links and the lower horizontal link. One link is grounded, namely the pedestal, and the right most link traces an approximate straight-line motion as indicated by the gratuitous slider joint below the right link.

The linkage in Figure I.30 is a generalization of the closed four-bar linkage to include rigid links with more than two revolute joints. Thus if n_i denotes the number of links with i joints, then the equations relating the number of sub links to the total number of links and joints are (Grübler, 1917):

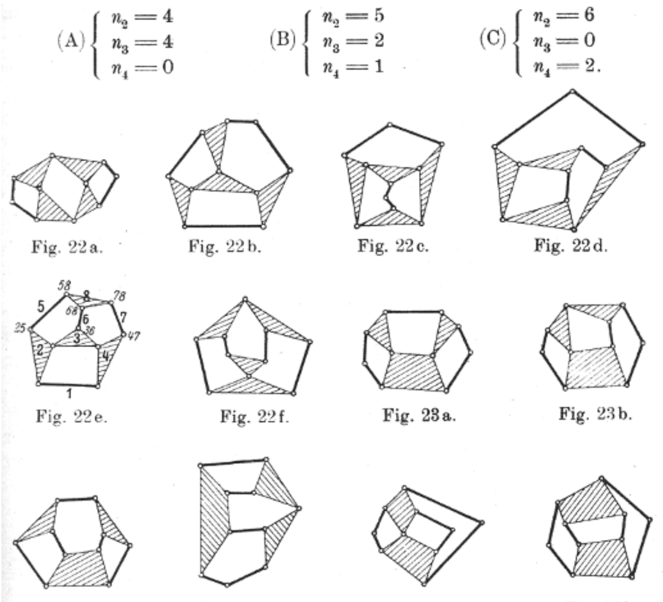

Figure I.32. Table of eight-bar linkages with one degree of freedom when one bar is grounded (Grübler, 1917)

$$n = \sum_{i=2} n_i, \tag{4}$$

$$r = \tfrac{1}{2} \sum_{i=2} i n_i; \quad (F = 1). \tag{5}$$

For example, in the case of the six-bar mechanism in Model S-32, we have $\{n = 6, n_2 = 4, n_3 = 2\}$, with $r = 7$, $F = 1$.

In the case of eight-link mechanisms, one can also have four-joint links. It is easy to show using the above equations that there are three classes of eight-link mechanisms:

$$\{n_2 = 4, n_3 = 4, n_4 = 0\},$$

$$\{n_2 = 5, n_3 = 2, n_4 = 1\},$$

$$\{n_2 = 6, n_3 = 0, n_4 = 2\}.$$

Within a single class of eight-link mechanisms there can be multiple distinct topologies as shown in Figure I.32 from Grübler (1917: Figures 22, 23).

In typical sketches of compound linkages, two-joint links are drawn as straight lines, three-joint links as triangles, and four-joint links as trapezoids.

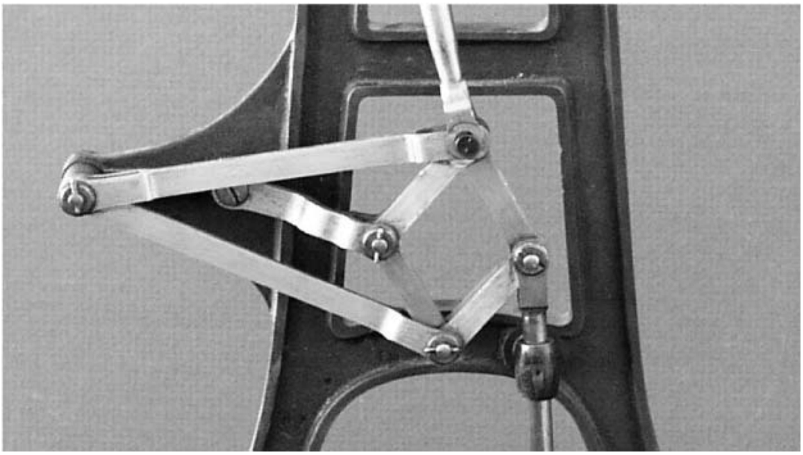

Figure I.33. Peaucellier exact straight-line mechanism with eight links and ten revolute joints: one degree of freedom with one link grounded. (Reuleaux–Voigt Model S-35, Cornell Kinematic Mechanisms Collection; See also KMODDL website)

The revolute joints are drawn as open circles. In actual compound mechanisms however, the links can have any shape.

An example of a compound mechanism is the straight-line mechanism of Peaucellier shown in Figure I.33 of Reuleaux–Voigt Model S-35.

This was the first recognized *exact*, planar, straight-line mechanism, traced by the right most pin joint. This mechanism has $n = 8$ links, and $r = 10$ turning joints (counting the four double pin joints and ignoring the upper crank arm and the lower slider arm which are not needed in the pure Peaucellier cell). For this arrangement, $F = 1$. The outer pin can trace either an exact straight line or an exact arc of a circle of any radius.

Finally we may apply Grübler's mobility criterion to one of Leonardo da Vinci's mechanisms from the *Codex Atlanticus*, called a lazy tongs or what one reference called 'Nürnberg shears' shown in Figure I.34. The vertical motion of the pin on the sliding block moves the rhombus shaped linkage. This linkage appears in two different folios. The incomplete linkage (CA Folio 16r) contains six links and seven rotary joints, double counting the two joints at the top and bottom that each connect three links. Using Grübler's equation (2) we obtain a degree of freedom, $F = 1$, as expected.

Grübler's generalization of the possibilities of compound kinematic mechanisms did not appear in Reuleaux's work. Reuleaux can be credited with using topological ideas in kinematics to encompass a large class of mechanisms within a given sequence of joint constraints in a kinematic chain. Mathematically Reuleaux was likely influenced by the geometric kinematics of Euler

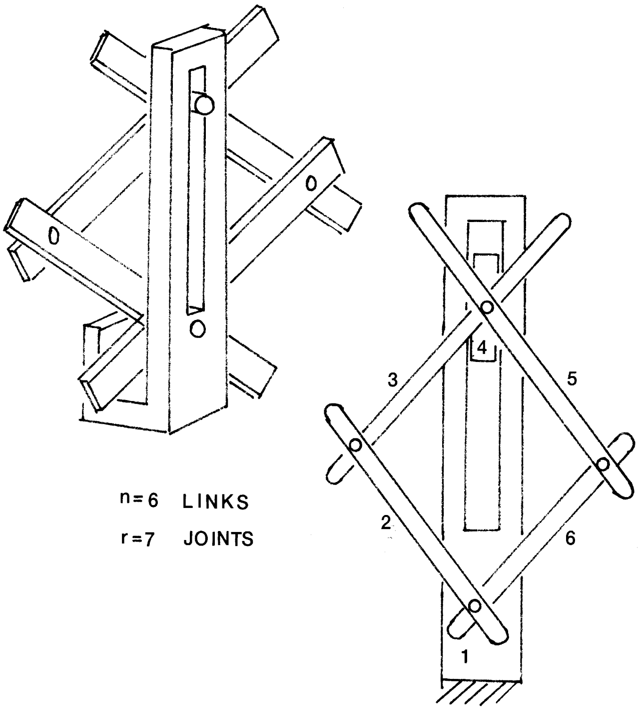

Figure I.34. Sketch of Leonardo's 'lazy tongs' or 'Nürnberg shears' mechanism of Leonardo da Vinci; six links and seven revolute joints

in 1765, Poinsot (1834) and Aronhold (1872) in kinematics of rigid bodies as he mentioned in his *Kinematics of Machinery* (1876). Reuleaux was also preoccupied with a search for a method of machine classification as again illustrated in the opening chapter of his book. He rejected the schemes of Monge, Willis, Belanger, Haton and other French writers in the mid 19th century based on motion changing principles. He instead settled on the more abstract method of networks of geometric constraints that later inspired other theoreticians in mechanism theory.

The concept of the kinematic chain idea brought mechanism theory into analogy with electrical circuit theory. Reuleaux, with few exceptions, did not treat mechanisms with more than one circuit or one degree of freedom, where one link is active and the others are follower links. However, there are differential mechanisms, used in automobile transmissions, which have two input links. Nor did Reuleaux develop an energy theorem for his kinematic circuit analogous to Kirchhoff's circuit law. The extension of the kinematic chain to multi-circuit mechanisms, which Reuleaux called 'compound chains', was

developed later in the 20th century in the form of network theory, graph theory, and screw theory (see e.g. Davies, 1983; Phillips, 1990).

The Reuleaux 'School' of kinematics that included Kennedy (1886) in England and Burmester (1888), Hartmann (1913) and Grübler (1917) in Germany, and Masi (1883) in Italy, influenced the ideas, constructs and nomenclature of kinematics to this day.

I.9 SUMMARY

In reviewing the career of Leonardo da Vinci we have tried to place his work in the context of other Renaissance artist-architect-engineers. Though not unique as an illustrator and inventor of machines, his machine drawings began a four-century evolution in machine theory in conceptualizing the machine as a set of basic machine elements and kinematic mechanisms that matured into the theories of Robert Willis and Franz Reuleaux. Both Leonardo and Reuleaux were intrigued by the nature of invention of technology. This theme will be further developed in Part II of this book.

In the Machine Age of the early 19th century, the manufacture of machines was a workshop process passed on to apprentices by master mechanics and engineers who often kept their methods secret and guarded against use by their competitors. The steam engine however, sparked not only a revolution in the creation of a mobile energy source, but also in the methods of creating new machines. The wresting of machine design from the workshop began in the Ecole Polytechnique in Paris in the late 18th century with the work of Monge and Hachette, and later by Ampere and Lanz and Betancourt. These ideas were further developed in Britain, especially in the work of Robert Willis [1800–1875] and William Rankine [1820–1872] and in Germany by Ferdinand Redtenbacher [1809–1863] of the Polytechnic School at Karlsruhe whose student was Franz Reuleaux. Reuleaux created a more abstract language for describing machines. He was also the first engineer to use topological ideas in kinematics as a method to enumerate the set of possibilities for the invention of new machines.

In this review of the life and work of Leonardo da Vinci and Franz Reuleaux we have encountered many other engineers and machine designers who were part of this evolution of our knowledge of machines today. In Part II we present a review of the wider history of machine evolution and the role that mathematics, mechanics and art played in this history. We will also try to evaluate the roles and contributions of Leonardo and Reuleaux in the design of machines during this period.